US009465001B2

(12) **United States Patent**
Stanley

(10) **Patent No.: US 9,465,001 B2**
(45) **Date of Patent: Oct. 11, 2016**

(54) **CONDUCTIVE LIQUID PROPERTY MEASUREMENT USING VARIABLE PHASE MIXING**

(71) Applicant: **Bourns, Inc.**, Riverside, CA (US)

(72) Inventor: **James Gregory Stanley**, Novi, MI (US)

(73) Assignee: **BOURNS, INC.**, Riverside, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/855,027**

(22) Filed: **Sep. 15, 2015**

(65) **Prior Publication Data**

US 2016/0077030 A1 Mar. 17, 2016

Related U.S. Application Data

(60) Provisional application No. 62/050,656, filed on Sep. 15, 2014.

(51) **Int. Cl.**

G01R 35/00	(2006.01)
G01N 27/12	(2006.01)
G01N 27/22	(2006.01)

(52) **U.S. Cl.**

CPC ***G01N 27/122*** (2013.01); ***G01N 27/228*** (2013.01)

(58) **Field of Classification Search**

CPC G01N 27/122; G01N 27/227; G01N 27/228; G01N 33/18; G01R 35/005; G01R 27/28; G01R 27/32; G01R 27/60; G01R 1/28; G01R 1/072; G01R 1/067; G01R 1/073; G01R 23/20; G01R 31/022; G01R 31/021; G01R 31/1272; G01R 31/025; G01R 31/2886; G01R 29/24

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,577,612	A	12/1951	Fay
4,181,881	A	1/1980	Preikschat
4,238,726	A	12/1980	Ichijo
4,288,741	A	9/1981	Dechene et al.

(Continued)

FOREIGN PATENT DOCUMENTS

CA	1128772	A	8/1982
CN	1719265		1/2006
CN	102147382	A	8/2011

OTHER PUBLICATIONS

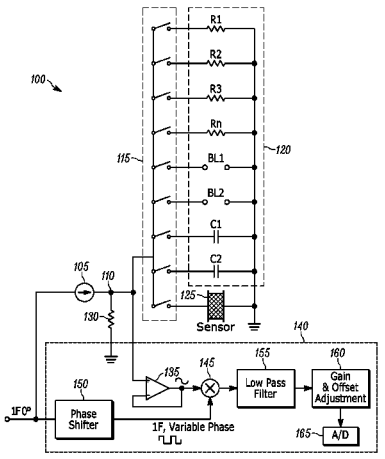
International Search Report and Written Opinion for Application No. PCT/US2015/050234 dated Dec. 23, 2015 (11 pages).

Primary Examiner — Son Le
Assistant Examiner — Thang Le
(74) *Attorney, Agent, or Firm* — Michael Best & Friedrich LLP

(57) **ABSTRACT**

A system and method for measuring an electrical characteristic of a fluid using a measuring circuit. In one implementation, the measuring circuit includes a sensing component, a current supply connected to the sensing component, a sensor switchably connected to the sensing component, an array of components switchably connected to the sensing component, and a monitoring circuit connected to the sensing component. A controller performs a calibration of the measuring circuit by switching parallel impedances in and out of the circuit while measuring voltages across the sensing component. The voltages are measured at at least two different phase angles that are determined by the calibration. Once voltages at different impedances and different phases are determined, the controller calculates a value of the electrical characteristic of the fluid by interpolating between lines of fixed capacitance or resistance.

20 Claims, 17 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

4,675,596	A	6/1987	Smith	
4,751,476	A	6/1988	Meijer	
5,014,011	A	5/1991	Colvin	
5,225,783	A	7/1993	Suzuki et al.	
5,235,267	A	8/1993	Schoneberg et al.	
5,268,642	A	12/1993	Uchidomi	
5,313,168	A	5/1994	Ogawa	
5,414,368	A	5/1995	Ogawa et al.	
5,594,163	A	1/1997	Suzuki	
6,265,883	B1	7/2001	Clark	
6,283,504	B1	9/2001	Stanley et al.	
6,320,393	B1	11/2001	Yasui et al.	
6,857,313	B2	2/2005	Williamson	
7,098,674	B2	8/2006	Stanley et al.	
7,180,306	B2	2/2007	Stanley et al.	
7,617,055	B2 *	11/2009	Henry	G01F 1/74 702/100
7,659,731	B2	2/2010	Lin et al.	
7,926,341	B2	4/2011	Boudaoud et al.	
2006/0186897	A1 *	8/2006	Niemann	G01N 11/16 324/633
2008/0264170	A1 *	10/2008	Abbott	G01N 29/022 73/590
2010/0188111	A1	7/2010	Fougere	
2010/0327884	A1	12/2010	McCall et al.	
2012/0326733	A1 *	12/2012	Kato	G01N 33/2852 324/674
2013/0291617	A1	11/2013	Boudaoud et al.	

* cited by examiner

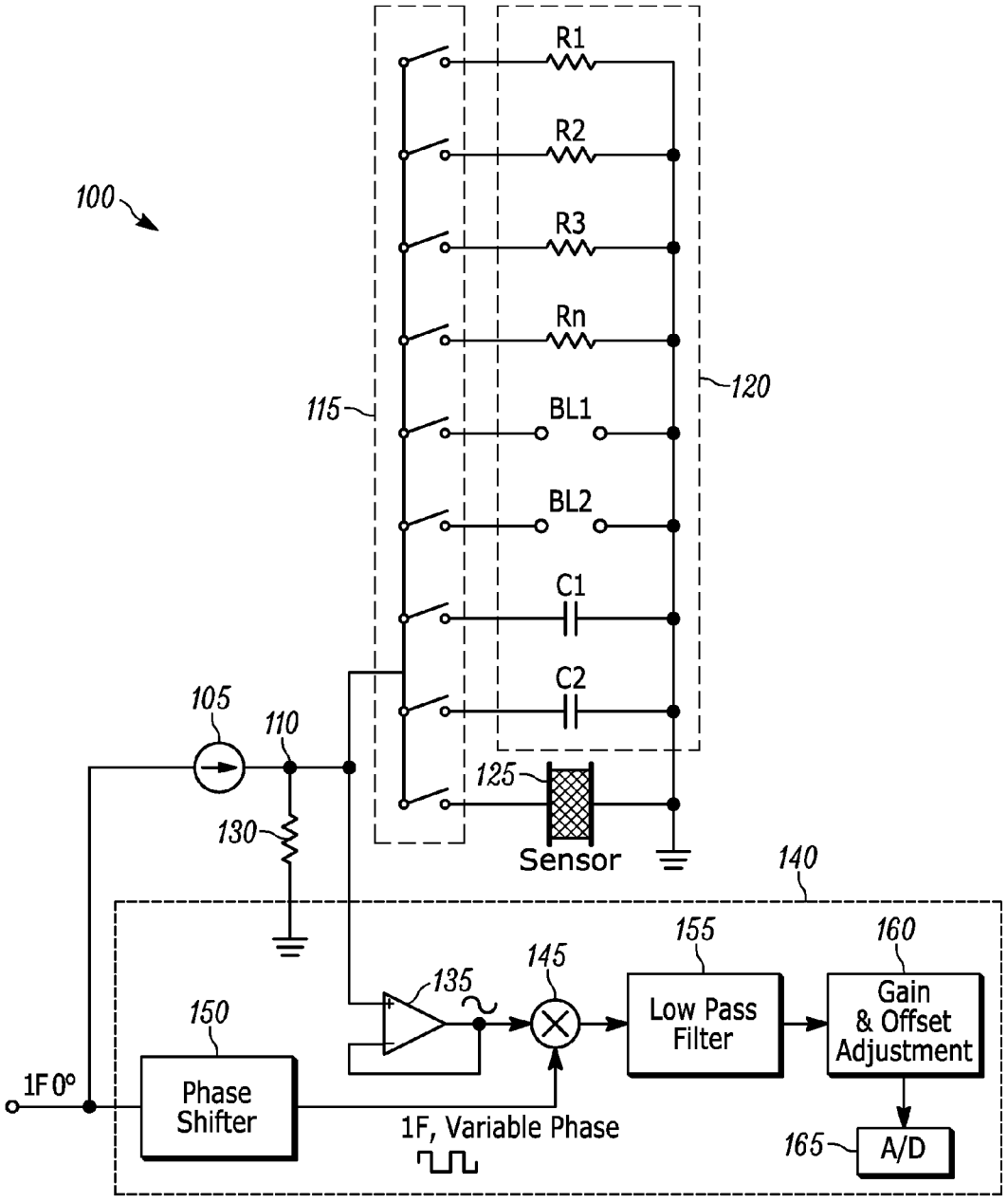

100
R1
R2
R3
Rn
BL1
BL2
C1
C2
115
120
105
110
125
130
Sensor
140
155
160
145
135
150
Low Pass Filter
Gain & Offset Adjustment
1F 0°
Phase Shifter
1F, Variable Phase
165
A/D

FIG. 1

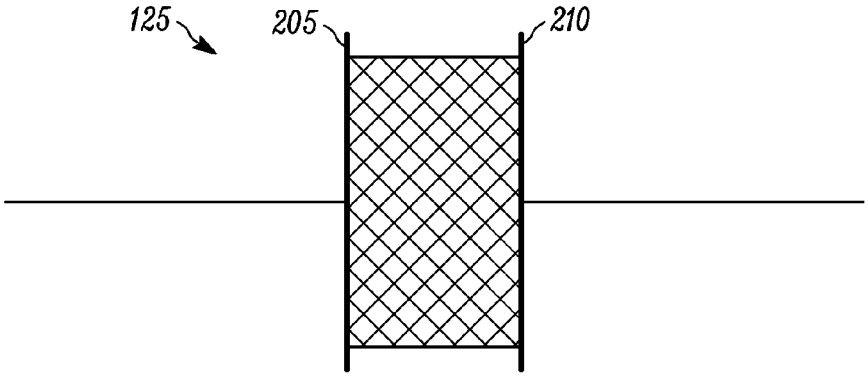


FIG. 2A

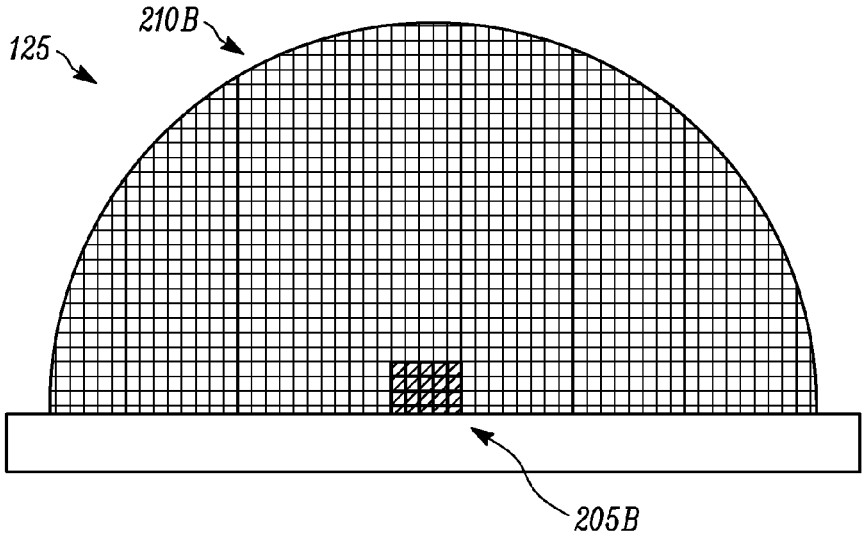


FIG. 2B

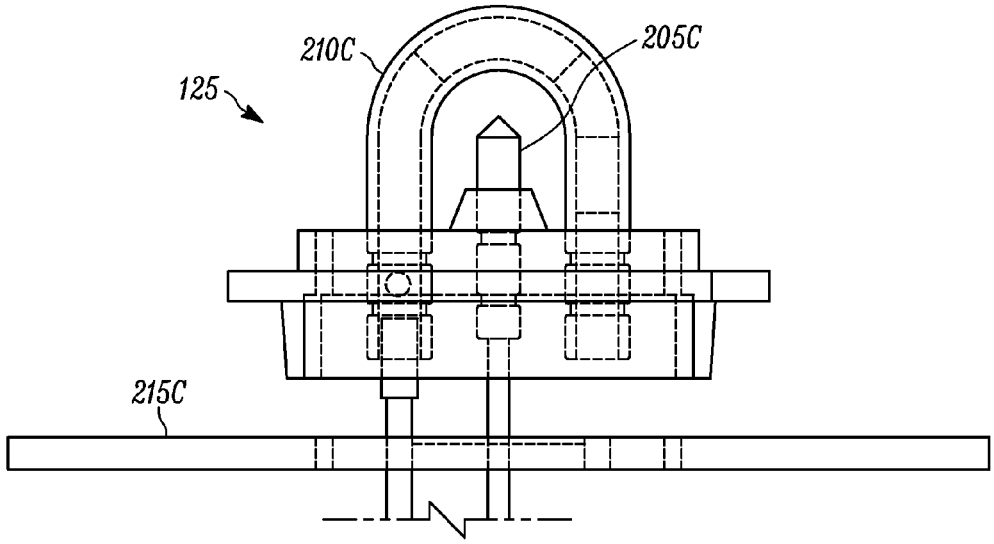


FIG. 2C

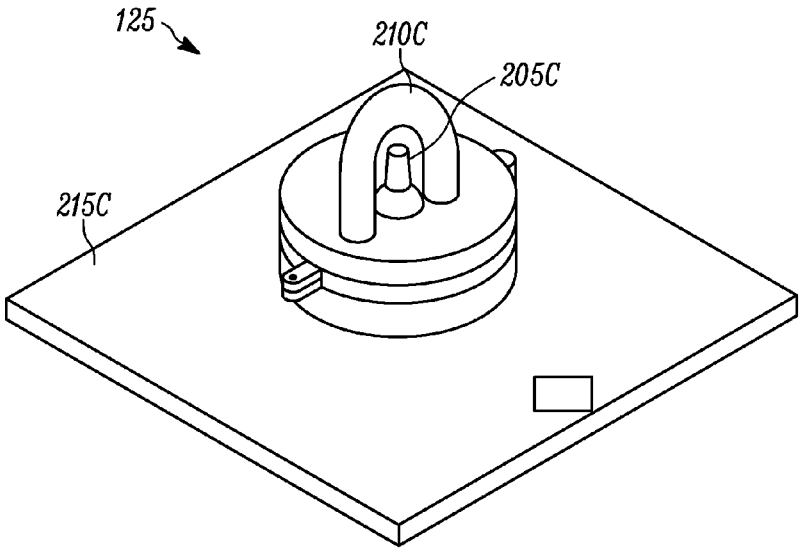


FIG. 2D

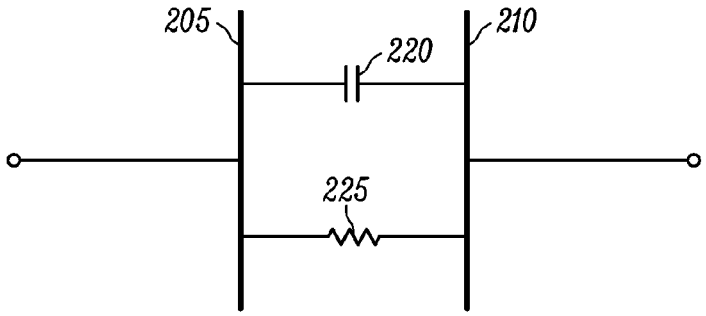


FIG. 3A

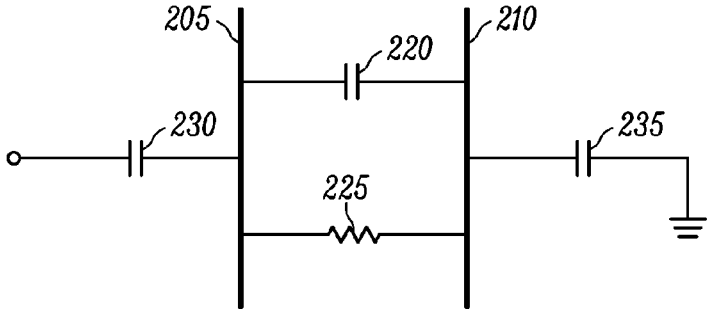


FIG. 3B

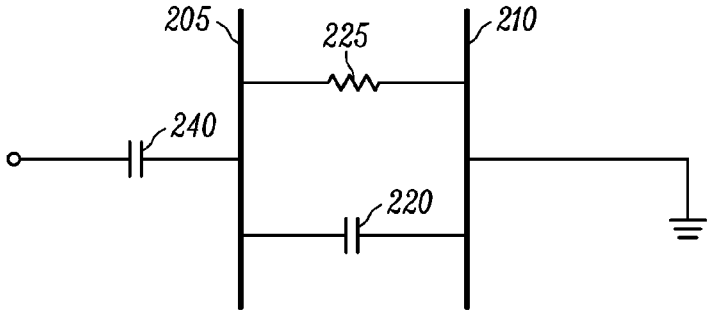


FIG. 3C

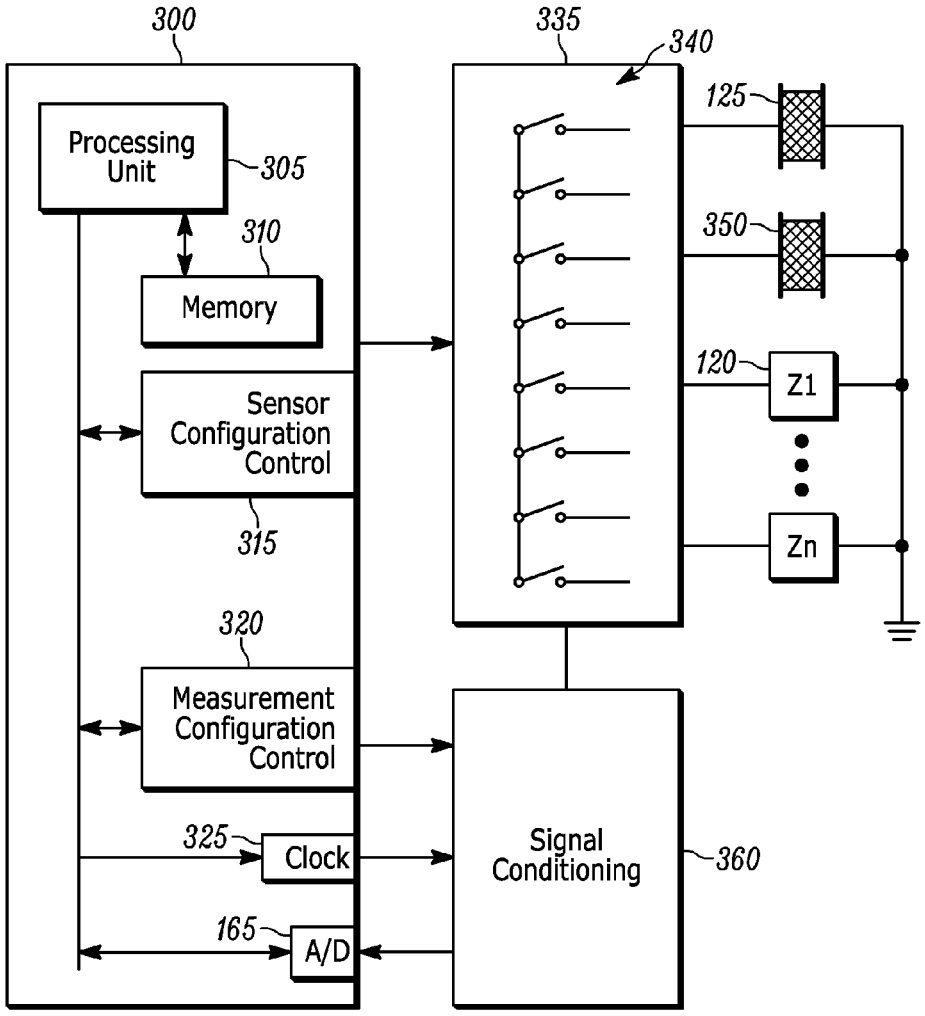

300
335
340
125
Processing Unit
305
310
350
Memory
120
Z1
Sensor Configuration Control
315
Zn
320
Measurement Configuration Control
325
Clock
Signal Conditioning
360
165
A/D

FIG. 4

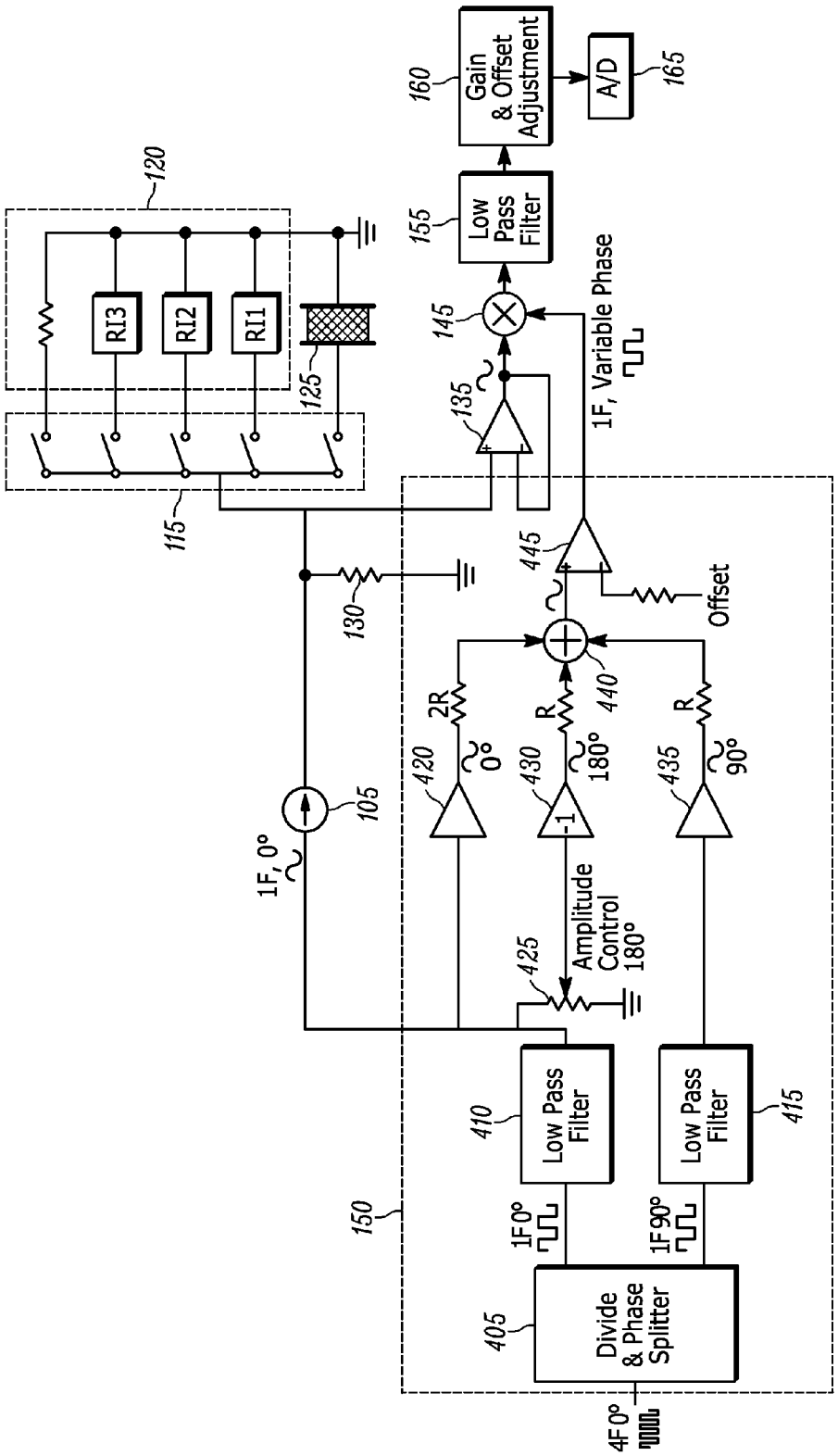

160
Gain & Offset Adjustment
A/D
165
155
Low Pass Filter
145
1F, Variable Phase
135
120
RI3
RI2
RI1
125
115
130
445
Offset
2R
R
R
440
420
430
435
0°
180°
90°
105
1F, 0°
-1
Amplitude Control 180°
425
410
Low Pass Filter
Low Pass Filter
415
150
1F0°
1F90°
405
Divide & Phase Splitter
4F0°

FIG. 5

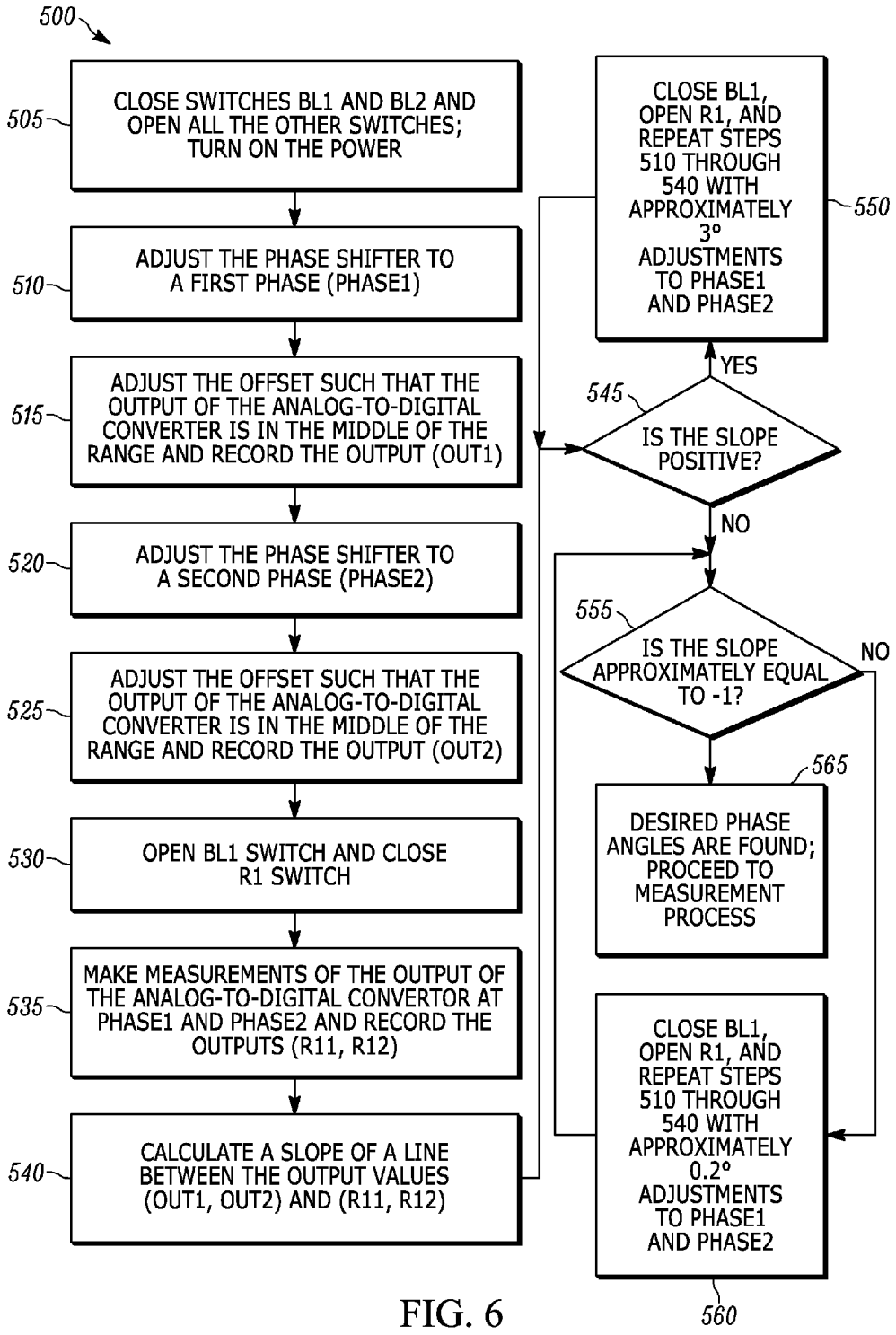

500
505
CLOSE SWITCHES BL1 AND BL2 AND OPEN ALL THE OTHER SWITCHES; TURN ON THE POWER
510
ADJUST THE PHASE SHIFTER TO A FIRST PHASE (PHASE1)
515
ADJUST THE OFFSET SUCH THAT THE OUTPUT OF THE ANALOG-TO-DIGITAL CONVERTER IS IN THE MIDDLE OF THE RANGE AND RECORD THE OUTPUT (OUT1)
520
ADJUST THE PHASE SHIFTER TO A SECOND PHASE (PHASE2)
525
ADJUST THE OFFSET SUCH THAT THE OUTPUT OF THE ANALOG-TO-DIGITAL CONVERTER IS IN THE MIDDLE OF THE RANGE AND RECORD THE OUTPUT (OUT2)
530
OPEN BL1 SWITCH AND CLOSE R1 SWITCH
535
MAKE MEASUREMENTS OF THE OUTPUT OF THE ANALOG-TO-DIGITAL CONVERTOR AT PHASE1 AND PHASE2 AND RECORD THE OUTPUTS (R11, R12)
540
CALCULATE A SLOPE OF A LINE BETWEEN THE OUTPUT VALUES (OUT1, OUT2) AND (R11, R12)
545
IS THE SLOPE POSITIVE?
YES
NO
550
CLOSE BL1, OPEN R1, AND REPEAT STEPS 510 THROUGH 540 WITH APPROXIMATELY 3° ADJUSTMENTS TO PHASE1 AND PHASE2
555
IS THE SLOPE APPROXIMATELY EQUAL TO -1?
NO
565
DESIRED PHASE ANGLES ARE FOUND; PROCEED TO MEASUREMENT PROCESS
560
CLOSE BL1, OPEN R1, AND REPEAT STEPS 510 THROUGH 540 WITH APPROXIMATELY 0.2° ADJUSTMENTS TO PHASE1 AND PHASE2

FIG. 6

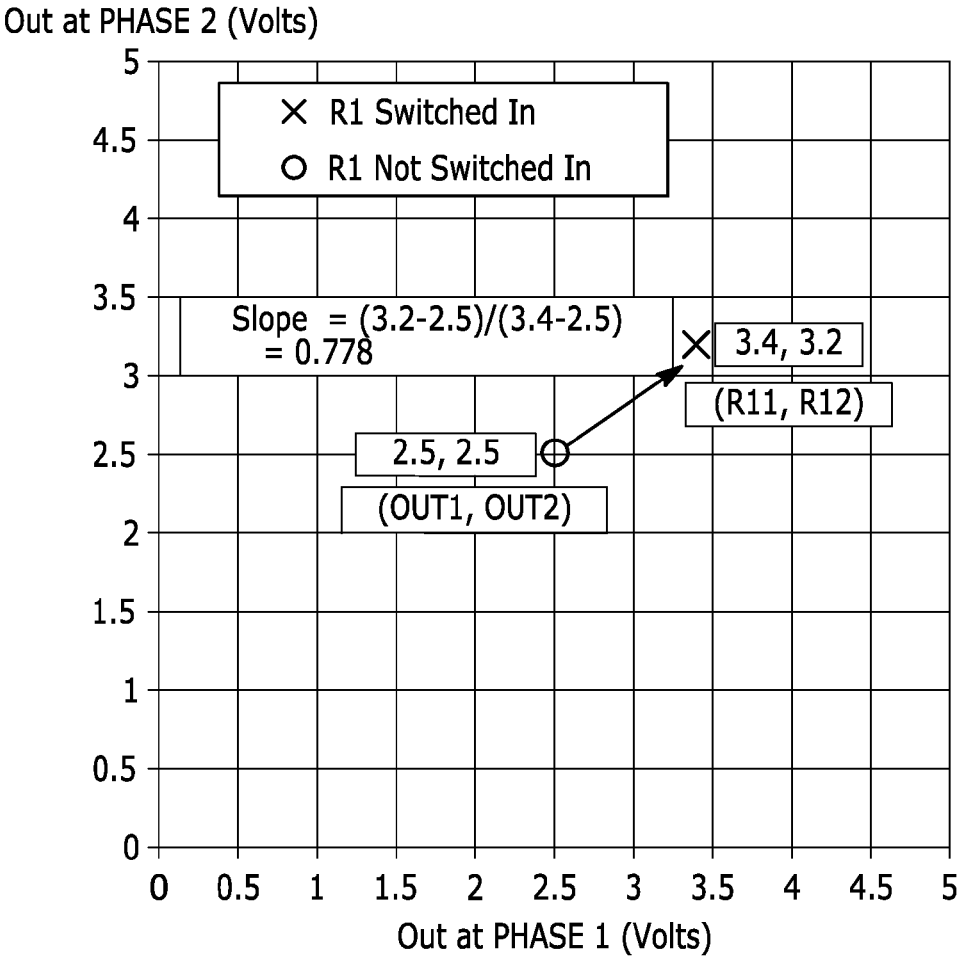

Out at PHASE 2 (Volts)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
R1 Switched In
R1 Not Switched In
Slope = (3.2-2.5)/(3.4-2.5)
= 0.778
3.4, 3.2
(R11, R12)
2.5, 2.5
(OUT1, OUT2)
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
Out at PHASE 1 (Volts)

FIG. 7

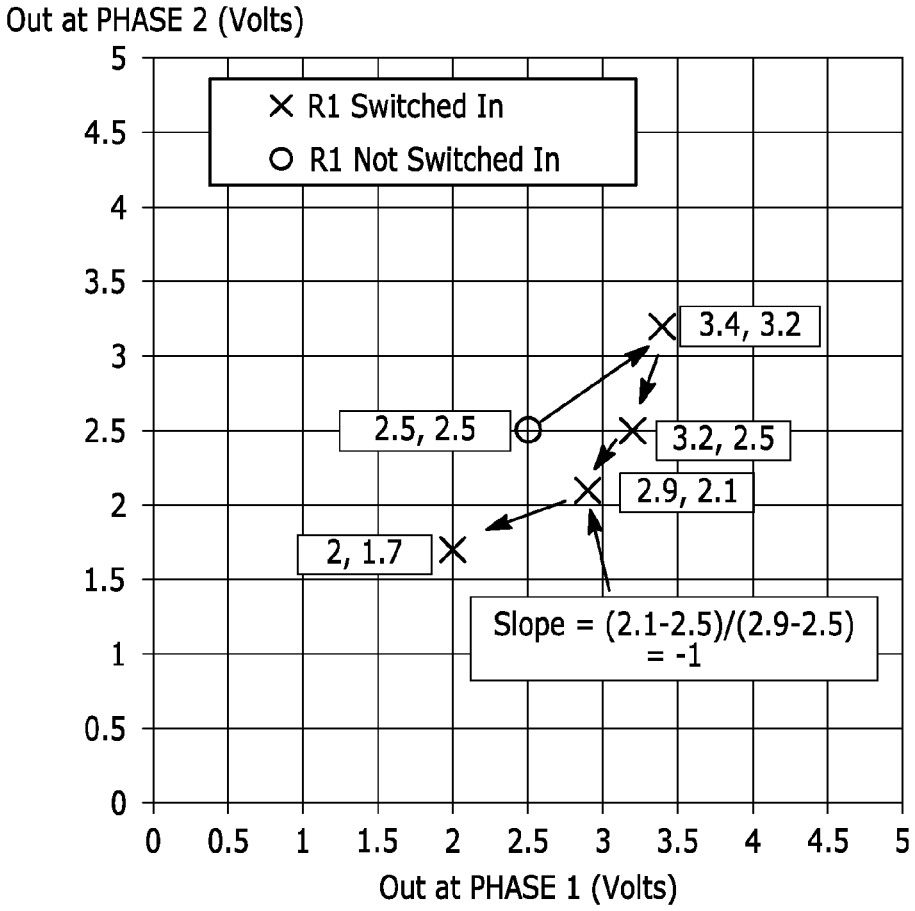

Out at PHASE 2 (Volts)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
R1 Switched In
R1 Not Switched In
3.4, 3.2
2.5, 2.5
3.2, 2.5
2.9, 2.1
2, 1.7
Slope = (2.1-2.5)/(2.9-2.5)
= -1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Out at PHASE 1 (Volts)

FIG. 8

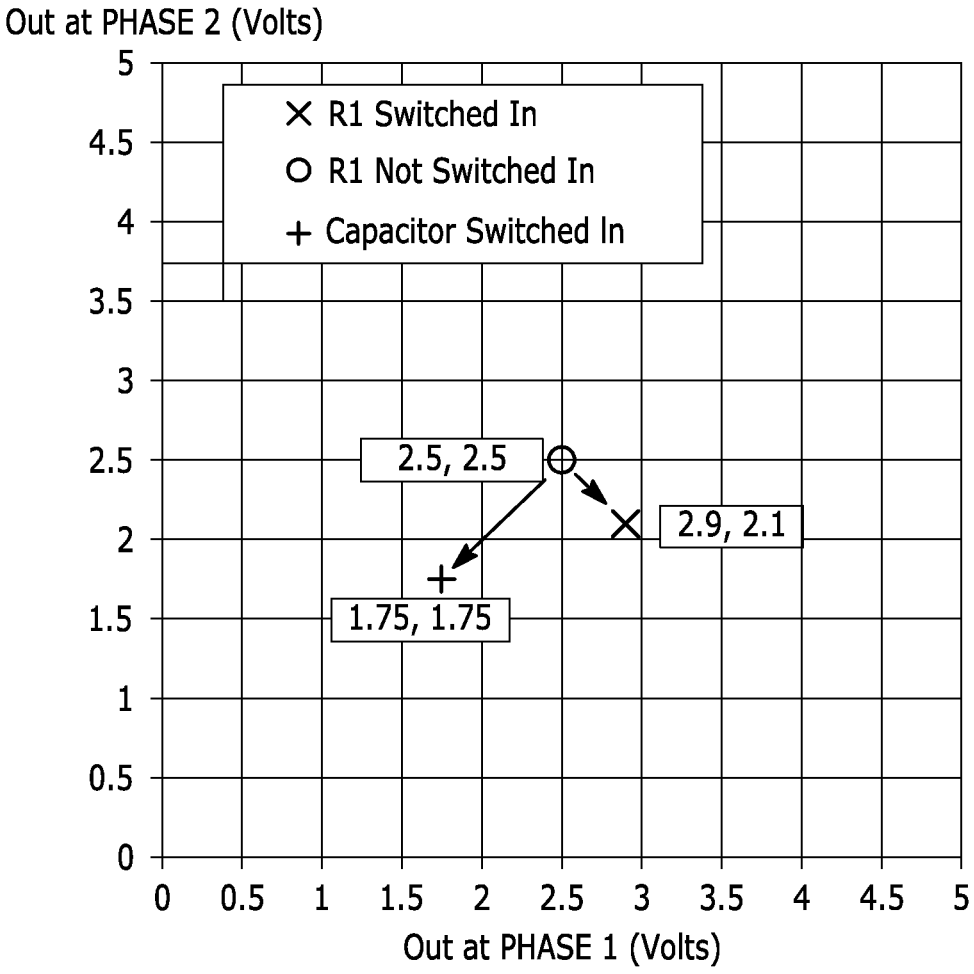

Out at PHASE 2 (Volts)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
R1 Switched In
R1 Not Switched In
Capacitor Switched In
2.5, 2.5
2.9, 2.1
1.75, 1.75
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Out at PHASE 1 (Volts)

FIG. 9

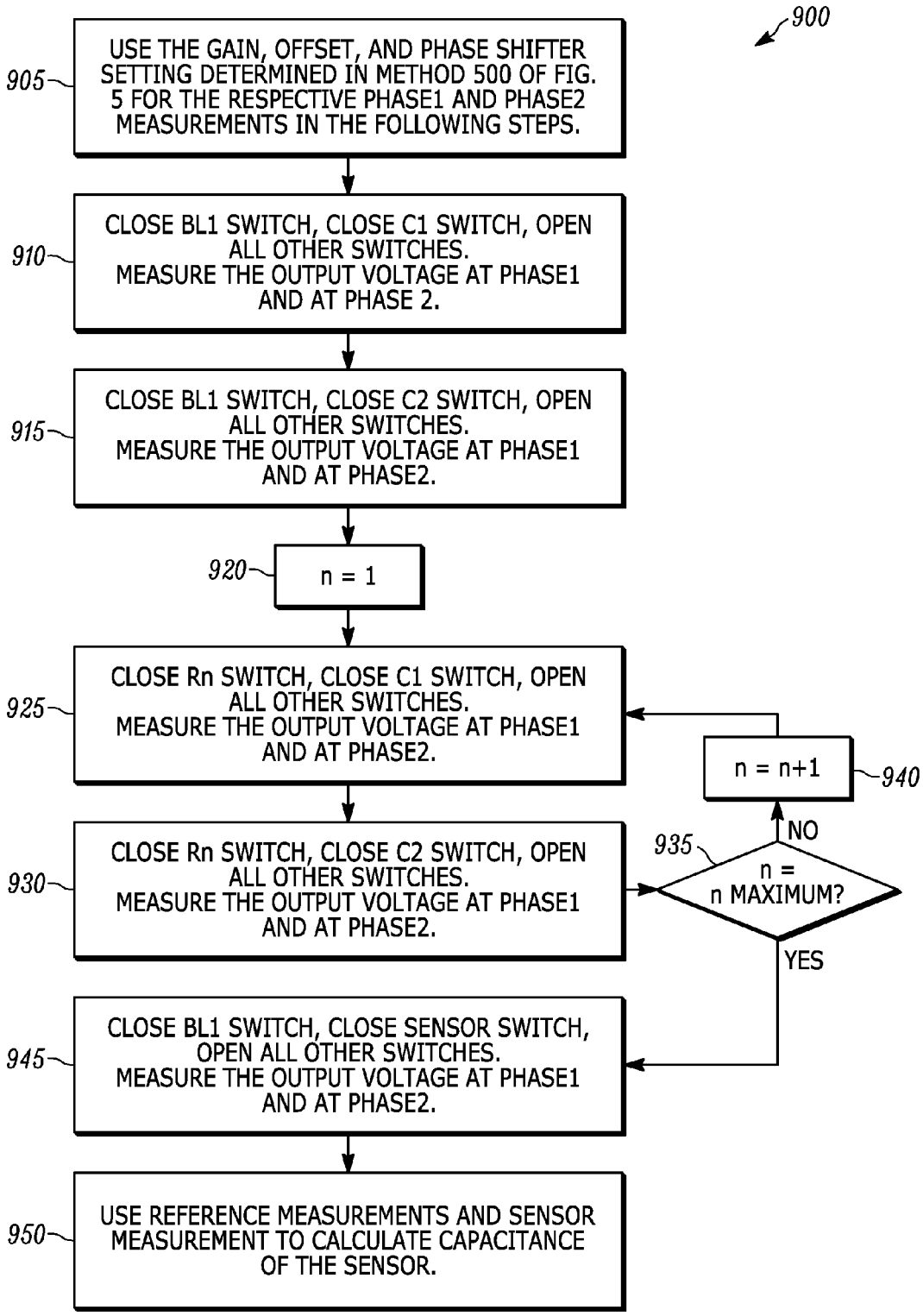

900
USE THE GAIN, OFFSET, AND PHASE SHIFTER SETTING DETERMINED IN METHOD 500 OF FIG. 5 FOR THE RESPECTIVE PHASE1 AND PHASE2 MEASUREMENTS IN THE FOLLOWING STEPS.
905
CLOSE BL1 SWITCH, CLOSE C1 SWITCH, OPEN ALL OTHER SWITCHES. MEASURE THE OUTPUT VOLTAGE AT PHASE1 AND AT PHASE 2.
910
CLOSE BL1 SWITCH, CLOSE C2 SWITCH, OPEN ALL OTHER SWITCHES. MEASURE THE OUTPUT VOLTAGE AT PHASE1 AND AT PHASE2.
915
n = 1
920
CLOSE Rn SWITCH, CLOSE C1 SWITCH, OPEN ALL OTHER SWITCHES. MEASURE THE OUTPUT VOLTAGE AT PHASE1 AND AT PHASE2.
925
CLOSE Rn SWITCH, CLOSE C2 SWITCH, OPEN ALL OTHER SWITCHES. MEASURE THE OUTPUT VOLTAGE AT PHASE1 AND AT PHASE2.
930
n = n MAXIMUM?
935
NO
YES
n = n+1
940
CLOSE BL1 SWITCH, CLOSE SENSOR SWITCH, OPEN ALL OTHER SWITCHES. MEASURE THE OUTPUT VOLTAGE AT PHASE1 AND AT PHASE2.
945
USE REFERENCE MEASUREMENTS AND SENSOR MEASUREMENT TO CALCULATE CAPACITANCE OF THE SENSOR.
950

FIG. 10

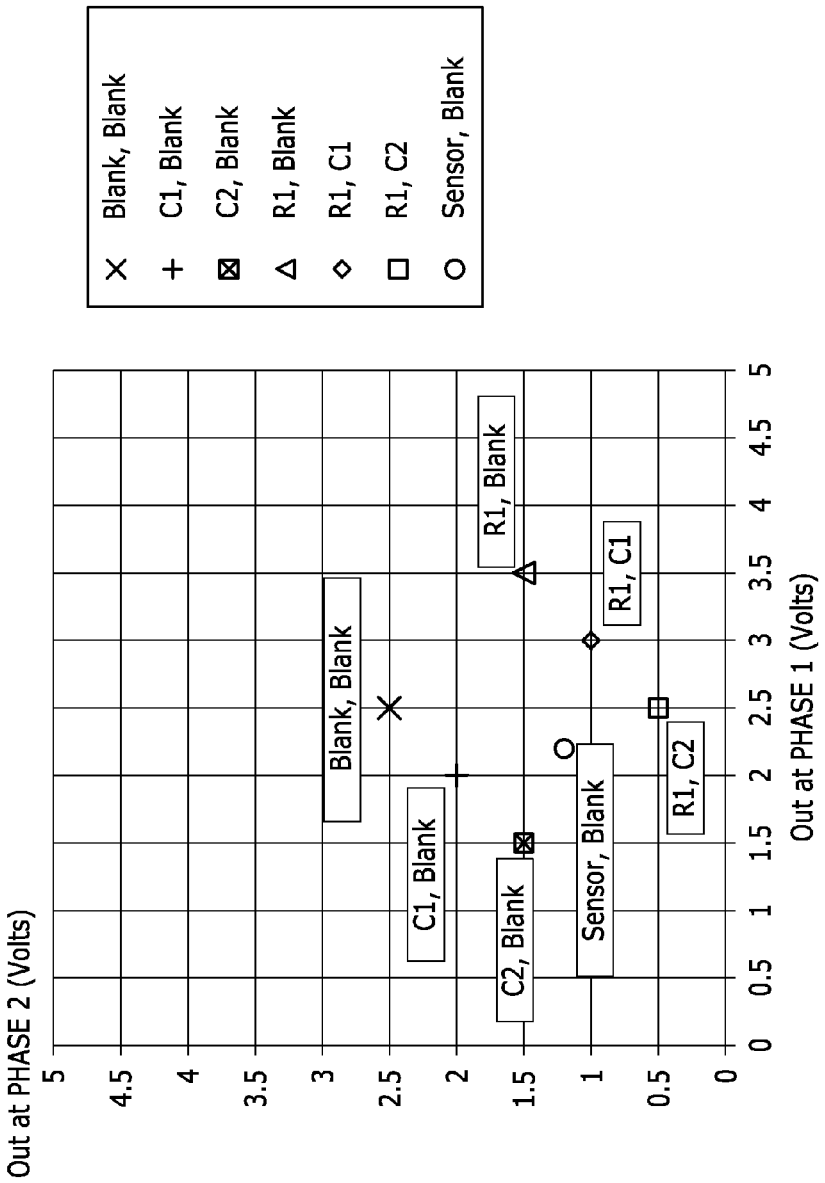

Blank, Blank
C1, Blank
C2, Blank
R1, Blank
R1, C1
R1, C2
Sensor, Blank
Out at PHASE 2 (Volts)
Out at PHASE 1 (Volts)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Blank, Blank
C1, Blank
C2, Blank
Sensor, Blank
R1, C2
R1, C1
R1, Blank

FIG. 11

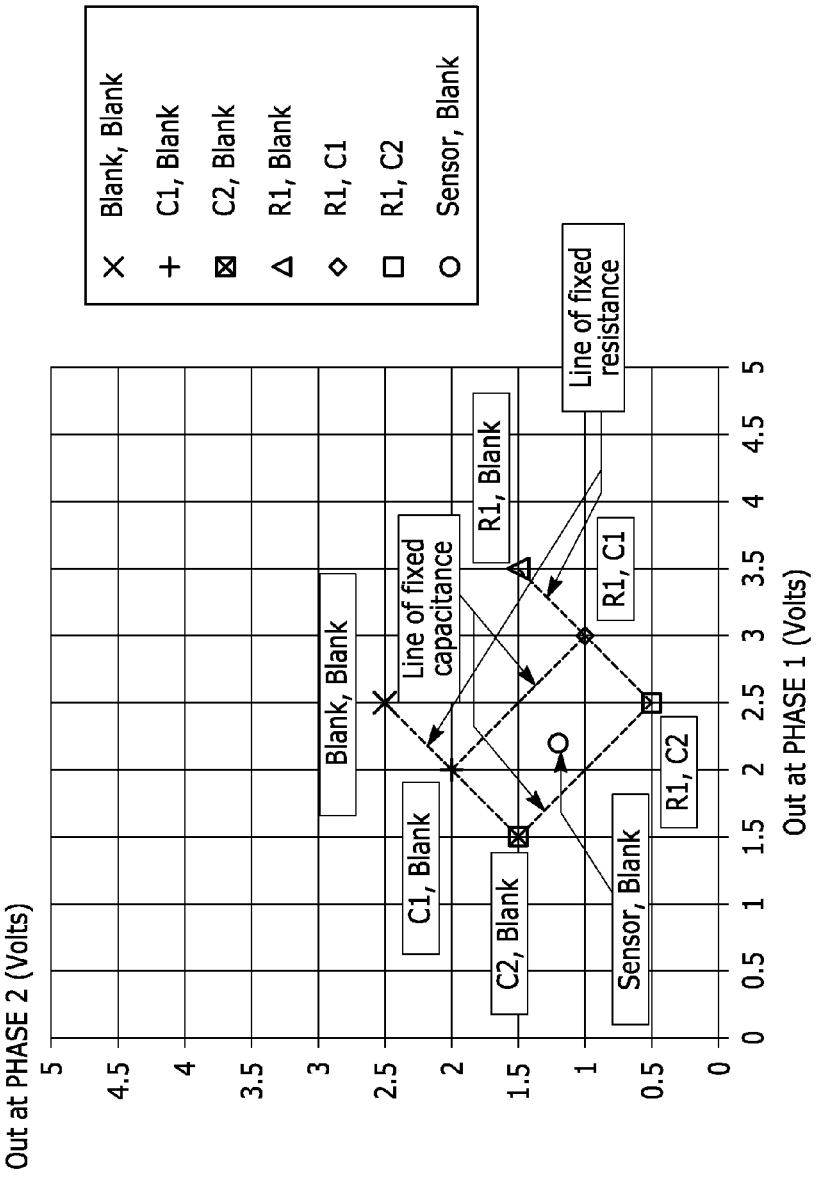

Blank, Blank
C1, Blank
C2, Blank
R1, Blank
R1, C1
R1, C2
Sensor, Blank
Line of fixed resistance
Line of fixed capacitance
Out at PHASE 2 (Volts)
Out at PHASE 1 (Volts)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

FIG. 12

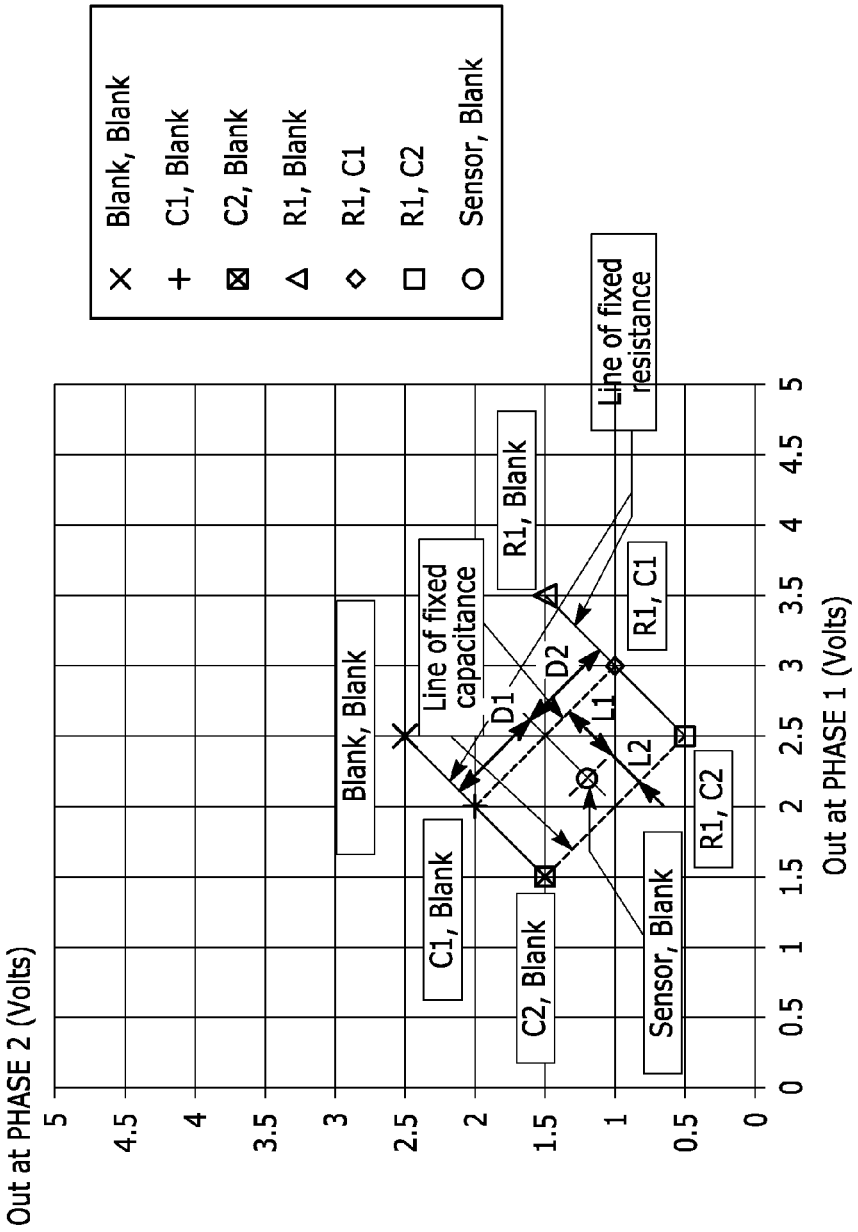

Blank, Blank
C1, Blank
C2, Blank
R1, Blank
R1, C1
R1, C2
Sensor, Blank
Out at PHASE 2 (Volts)
Out at PHASE 1 (Volts)
Line of fixed capacitance
Line of fixed resistance
D1
D2
L1
L2
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

FIG. 13

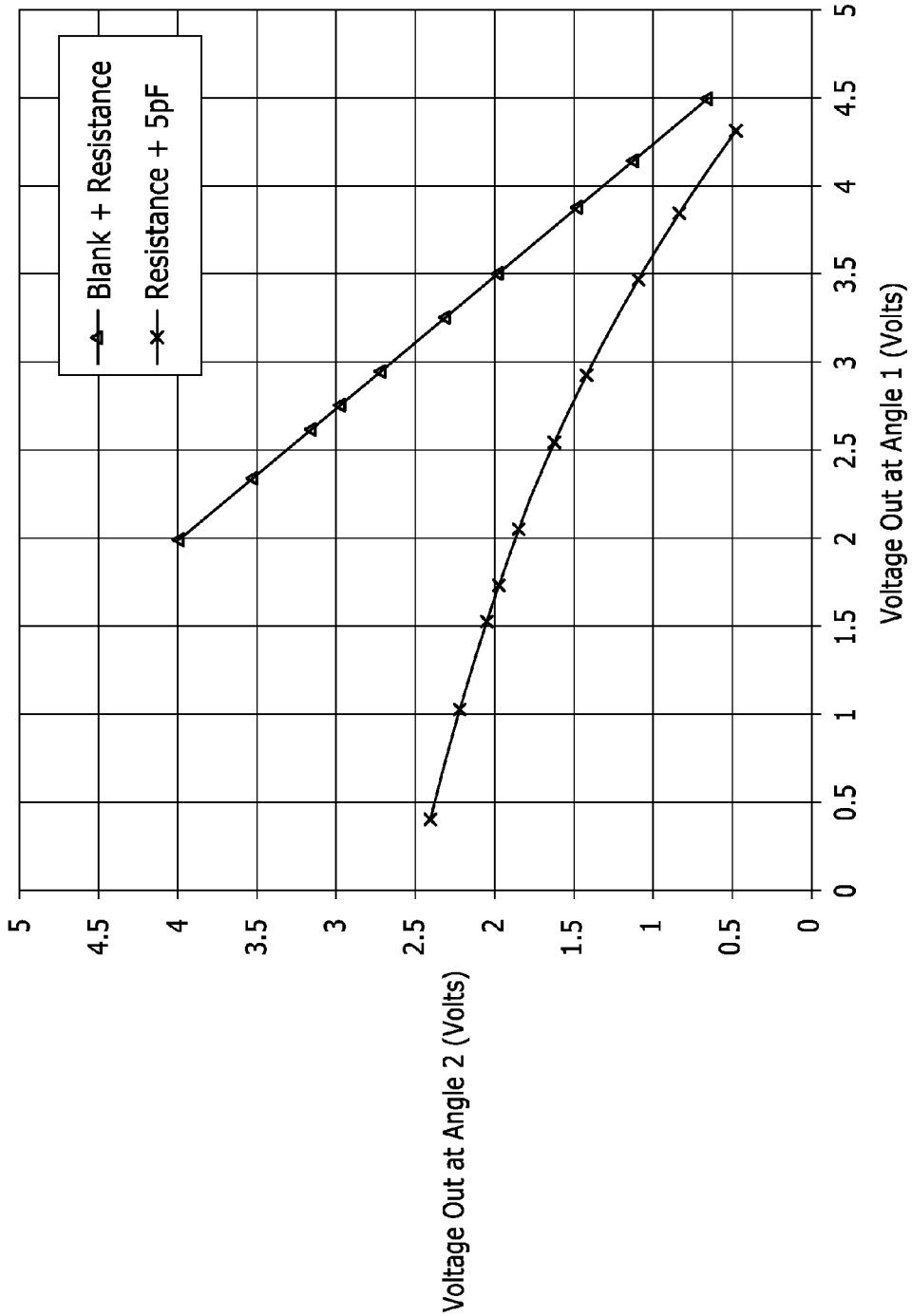

Blank + Resistance
Resistance + 5pF
Voltage Out at Angle 1 (Volts)
Voltage Out at Angle 2 (Volts)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

FIG. 14

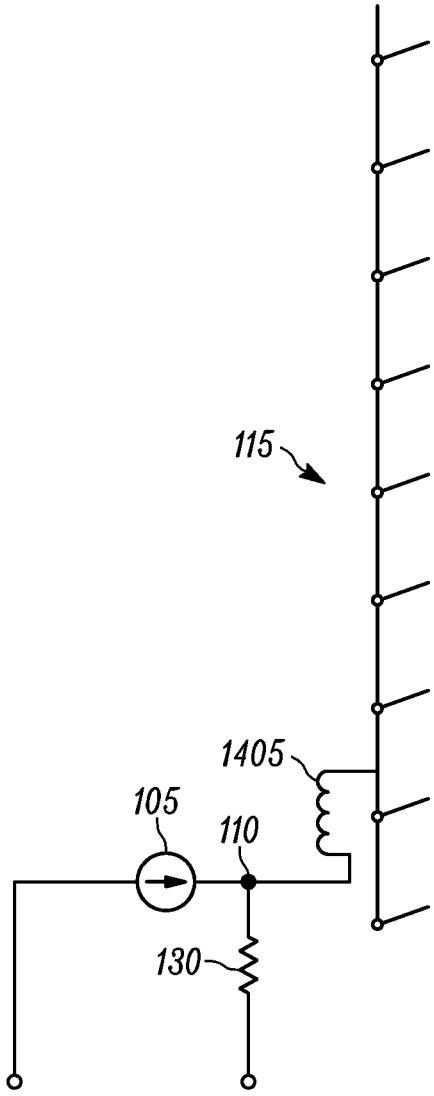


FIG. 15

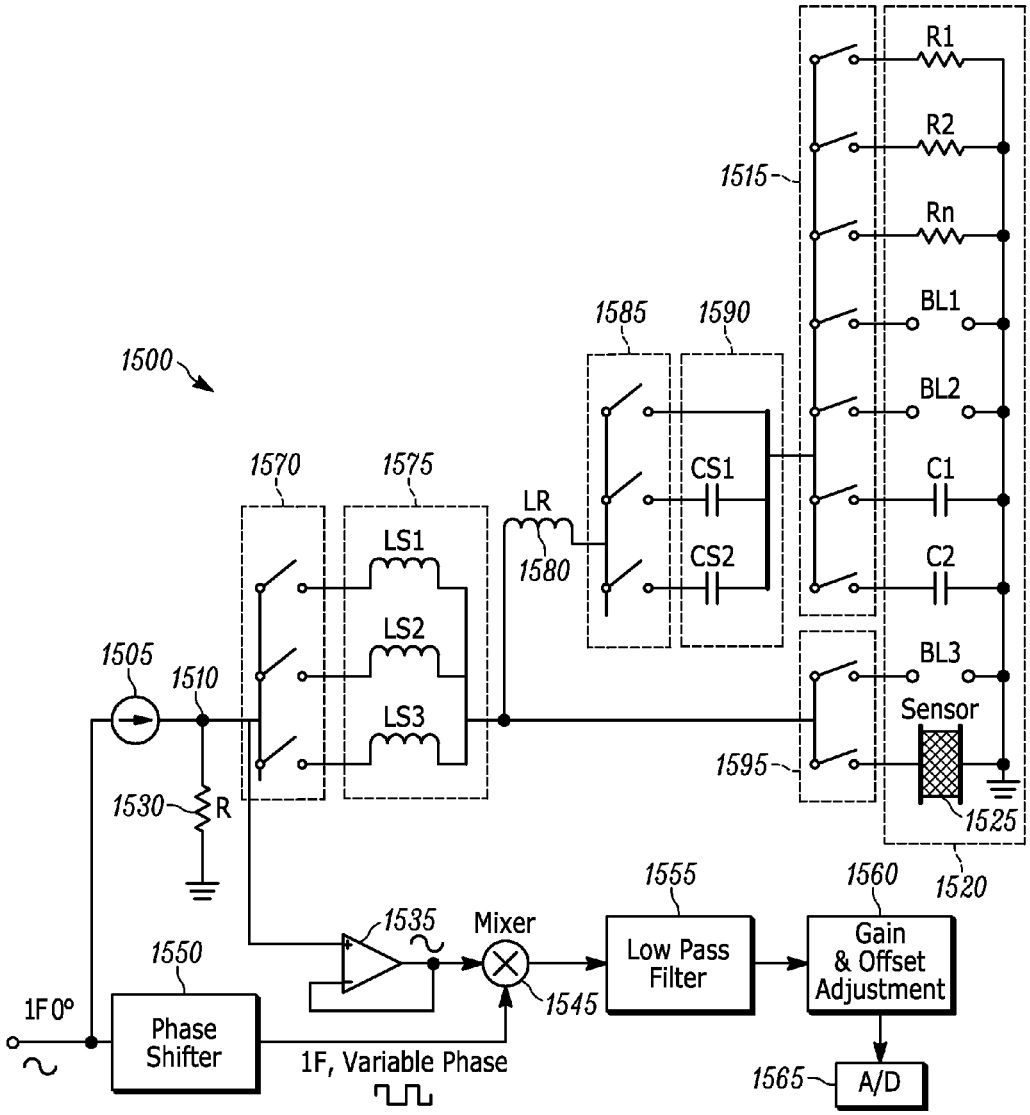

1500
1505
1510
1515
1520
1525
1530
R
1535
Mixer
1545
1550
1555
1560
1565
A/D
1570
1575
LS1
LS2
LS3
LR
1580
1585
1590
CS1
CS2
1595
R1
R2
Rn
BL1
BL2
BL3
C1
C2
Sensor
1F 0°
Phase Shifter
1F, Variable Phase
Low Pass Filter
Gain & Offset Adjustment

FIG. 16

CONDUCTIVE LIQUID PROPERTY MEASUREMENT USING VARIABLE PHASE MIXING

CROSS-REFERENCE TO RELATED CASES

This application claims the benefit of U.S. Provisional Patent Application No. 62/050,656, filed on Sep. 15, 2014, the entire contents of which are incorporated herein by reference.

BACKGROUND

Embodiments of the invention relate to systems, sensors, and methods for measuring electrical properties of a fluid.

SUMMARY

Traditional capacitive sensors are limited in their ability to measure capacitance when a highly conductive path is parallel to the capacitance, as occurs when measuring a highly conductive fluid. One embodiment of the invention provides a system for determining a capacitance of a sensor in a fluid despite wide fluctuations in the fluid's conductivity. Certain embodiments do not depend upon active circuit components to be nearly ideal. Also, the signal controls (i.e., offsets, amplitudes, phases) do not require extremely high resolution or tight control across temperatures. In some cases, embodiments may be implemented at a lower cost than existing system and sensors.

The invention provides a low-cost system for determining the dielectric constant of a fluid, despite wide fluctuations in a fluid's conductivity. Traditional low-cost capacitive sensors are limited in their ability to measure capacitance of a sensor in a fluid when a highly conductive path is parallel to the capacitance as occurs when measuring a highly conductive fluid. The dielectric constant and conductivity of a fluid may be used to determine when the fluid has an expected set of properties. For example, the dielectric constant and the conductivity of the fluid can be used to determine the concentration levels of the fluid or if the fluid meets a quality standard.

One embodiment provides a system for determining the electrical properties of a material such as a fluid. In particular, the system determines a conductivity and capacitance of a sensor immersed in a fluid such as a diesel exhaust fluid. The system uses a measuring circuit, which includes a current source, a fixed resistor, a switching array, and an array of components. The current source supplies current to the fixed resistor and to the array of components via the switching array. The switching array determines which components of the array of components are placed in parallel to the fixed resistor for measurement. The system uses a monitoring circuit, which includes a phase shifter, a mixer, and a gain and offset module. The phase shifter produces waveforms of varying phase, which are supplied to the mixer. The system also includes a measurement space, which includes coordinate pairs of measured voltages across the fixed resistor for a series of measurements where a plurality of components are placed in parallel to the fixed resistor. When the capacitive measurement sensor is switched to connect to the current source, a location of a point in the measurement space identifies a capacitance of the capacitive measurement sensor with respect to the coordinate pairs.

Another embodiment provides a method of determining a capacitance of a sensor, which is in contact with a liquid.

The method includes a sequence of steps to measure voltages across a fixed resistor for a series of measurements with a plurality of components placed in parallel to the fixed resistor. The measurements of the voltages are timed with a synchronous demodulation circuit such that signals at two phases produce an output where the signals change because of sensor capacitive changes independently of sensor resistive changes. The voltages across the fixed resistor when a capacitive measurement sensor is in parallel to the fixed resistor are measured for different phase signals. The capacitance of the capacitive measurement sensor is determined by interpolating between the voltage measurements.

Another embodiment provides a measurement system that is configured to determine various electrical characteristics of the fluid including, for example, dielectric constant and conductivity of the fluid. Using the capacitance of a sensor, a dielectric constant, or another measure related to the dielectric constant, of the fluid can be determined. The electrical characteristics of the fluid may be used to determine when the fluid has an expected set of physical properties. For example, the dielectric constant and the conductivity of the fluid can be used to determine the concentration level of the fluid or if the fluid meets a particular quality standard. In some cases, the measurement system provides the electrical properties of diesel exhaust fluid including a concentration and a purity of the diesel exhaust fluid.

Yet another embodiment provides a system for measuring an electrical characteristic of a fluid by separating a first orthogonal component of a signal change of a measurement signal and a second orthogonal component of the signal change of the measurement signal. The first orthogonal component is due to a change in resistance across a sensor and the second orthogonal component is due to a change in capacitance across the sensor. The system includes an array of components including the sensor. It also includes a mixer that mixes the measurement signal with a first phase signal and a second phase signal. The mixer outputs a first mixed signal related to the first phase signal and a second mixed signal relating to the second phase signal. The system also includes a controller that is configured to receive a signal indicative of the first mixed signal and the second mixed signal and to control the array of components to cause the signal change. Then the controller adjusts the first phase signal and the second phase signal such that when there is a change in the first orthogonal component, the first mixed signal is reduced and the second mixed signal is increased. The controller controls the array of components to cause additional signal changes and receives a plurality of mixed signals indicative of the additional signal changes at the first phase and the second phase. The controller determines the electrical characteristic of the fluid based on the plurality of mixed signals.

Yet another embodiment provides a method of measuring an electrical characteristic of a fluid with a measuring circuit that includes a sensing node, a sensor switchably connected to the sensing node, and an array of components switchably connected to the sensing node, and a controller. The method includes mixing a signal indicative of a voltage at the sensing node at a first configuration of the array of components with a first phase signal and a second phase signal to create a first set of reference signals. The signal is mixed, at a second configuration of the array of components, with the first phase signal and the second phase signal to create a second set of reference signals. The first phase signal and the second phase signal are adjusted until a relationship between the first set of reference signals and the second set of reference signals satisfies a condition. A plurality of con-

figurations are set for the array of components. The signal is mixed with the adjusted first phase signal and the adjusted second phase signal at each of the plurality of configurations of the array of components to create a plurality of sets of reference signals. The signal is mixed with the adjusted first phase signal and the adjusted second phase signal with the sensor connected to the sensing node to create a set of measurement voltages. The electrical characteristic of the fluid are determined based on a relationship between the plurality of sets of reference signals and the set of measurement voltages.

Yet still another embodiment provides a system for measuring an electrical characteristic of a fluid. The system includes a sensing node, a sensor connected, via a switching array, to the sensing node, and an array of components connected, via the switching array, to the sensing node. The array of components includes a plurality of impedances. The system also includes a monitoring circuit connected to the sensing node. The monitoring circuit is configured to input a plurality of signals at a plurality of phases and to output a signal related to a measurement signal at the sensing node. The system also includes a controller connected to the switching array and the monitoring circuit. The controller is configured to receive the plurality of signals at the plurality of phases and set a first phase and a second phase of an input signal to the monitoring circuit. The controller is also configured to measure, at a first calibration impedance of the plurality of impedances, a first calibration voltage at the first phase and a second calibration voltage at the second phase. The controller also is configured to measure, at a second calibration impedance of the plurality of impedances, a third calibration voltage at the first phase and a fourth calibration voltage at the second phase. The first phase and the second phase are adjusted until a relationship between the first calibration voltage, the second calibration voltage, the third calibration voltage, and the fourth calibration voltage satisfies a condition. The controller is configured to adjust the plurality of impedances by controlling the switching array to connect at least one component of the array of components to the sensing node in a parallel-type connection and to determine a first set of reference signals based on the signal when the switching array is configured to couple a first measuring impedance of the plurality of impedances to the sensing node. The controller is also configured to determine a second set of reference signals based on the signal when the switching array is configured to couple a second measuring impedance of the plurality of impedances to the sensing node and to determine a set of sensor voltages based on the signal when the switching array is configured to couple the sensor to the sensing node. The controller is further configured to determine an electrical characteristic of the sensor based on the first set of reference signals, the second set of reference signals, and the set of sensor voltages.

Other aspects and embodiments of the invention will become apparent by consideration of the detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram of a measuring circuit for measuring capacitance and resistance of a fluid in accordance with one embodiment.

FIG. **2**A is a schematic representation of a sensor in accordance with one embodiment.

FIG. **2**B is a side view of one type of the sensor.

FIG. **2**C is a side, partially cut-away view of one type of sensor

FIG. **2**D is a perspective view of the sensor shown in FIG. **2**C.

FIGS. **3**A-C illustrate electrical models of sensors in accordance with certain embodiments.

FIG. **4** is a block diagram of the measuring circuit of FIG. **1** including a controller.

FIG. **5** is a schematic representation of a phase shifter circuit of the measuring circuit of FIG. **1** in accordance with one embodiment.

FIG. **6** is a flowchart of a method of calibrating the measuring circuit of FIG. **1**.

FIG. **7** is a graph illustrating reference points of output voltages of the measuring circuit of FIG. **1**.

FIG. **8** is a graph illustrating changes in output voltages when a resistor is connected to the sensing node of the measurement circuit of FIG. **1** as measurement phases are incremented.

FIG. **9** is a graph illustrating changes in output voltages when a resistor and a capacitor are connected to the sensing node of the measurement circuit of FIG. **1**.

FIG. **10** is a flowchart of a method of measuring a capacitance of a sensor of the measuring circuit of FIG. **1**.

FIG. **11** is an exemplary graph of output voltages at multiple measurement phases with various components in connected to the sensing node.

FIG. **12** is a graph illustrating parallel fixed lines of capacitance based on the output voltages of FIG. **11**.

FIG. **13** is a graph illustrating interpolation between lines of fixed capacitance and lines of fixed resistance for determining the capacitance and the resistance of the fluid sensor with the measuring circuit of FIG. **1** according to one embodiment.

FIG. **14** is a graph illustrating non-linear effects of large changes in parallel resistance for the measuring circuit of FIG. **1**.

FIG. **15** is a schematic diagram of the measuring circuit of FIG. **1** including an inductor to balance parallel inductance in the circuit path of the sensor.

FIG. **16** is a block diagram of a measuring circuit for measuring capacitance and resistance of a fluid sensor in accordance with another embodiment.

DETAILED DESCRIPTION

Before any embodiments of the invention are explained in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the following drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways.

It should be noted that the phrase "series-type configuration" as used herein refers to a circuit arrangement where the described elements are arranged, in general, in a sequential fashion such that the output of one element is coupled to the input of another, but the same current may not necessarily pass through each element. For example, in a "series-type configuration," it is possible for additional circuit elements to be connected in parallel with one or more of the elements in the "series-type configuration." Furthermore, additional circuit elements can be connected at nodes in the series-type configuration such that branches in the circuit are present. Therefore, elements in a series-type configuration do not necessarily form a true "series circuit."

Additionally, the phrase "parallel-type configuration" as used herein refers to a circuit arrangement where the described elements are arranged, in general, in a manner such that one element is connected to another element, such that the circuit forms a parallel branch of the circuit arrangement. In such a configuration, the individual elements of the circuit may not necessarily have the same potential difference across them individually. For example, in a parallel-type configuration of the circuit it is possible for two circuit elements that are in parallel with one another to be connected in series with one or more additional elements of the circuit. Therefore, a circuit in a "parallel-type configuration" can include elements that do not necessarily individually form a true parallel circuit.

It should also be noted that the phrases related to measuring "capacitance," "resistance," "dielectric constant," "conductivity," or "electrical characteristics of a fluid" as used herein, do not necessarily require that the absolute values of those measures are calculated. These terms may refer to measures that are related to the absolute values of these measures. For example, a system the measures the "dielectric constant" of a fluid may not actually calculate the dielectric constant of a fluid, but rather it may make a measurement of a quantity, such as capacitance, that varies with the dielectric constant of the fluid. And, as a further example, measuring "capacitance" may refer to making a measurement that varies with the absolute capacitance.

FIG. **1** is a block diagram of a measuring circuit **100** according to one embodiment. An output of a current source **105** (e.g., a transconductance amplifier) is connected to a sensing node **110**. The sensing node **110** connects to a switching array **115**. The switching array **115** connects to an array of components **120**, whose other terminals are connected to ground. The array of components **120** includes a plurality of components that allow multiple impedances (Z**1** . . . Zn) to be selected including resistors (R**1**, R**2**, . . . Rn), each having different resistances. In other embodiments, a single device can replace the plurality of resistors (R**1**, R**2**, . . . Rn). In one example, a voltage-controlled, variable resistor may be used and may be implemented using a field effect transistor. The array of components **120** also includes multiple capacitors (C**1** and C**2**). The switching array **115** also connects to one or more blank switches (BL**1**, BL**2**). The blank switches are connected to pads on a printed circuit board where no component is electrically connected. The switching array **115** also connects to a sensor **125**, whose other terminal is connected to ground.

The switching array **115** creates different configurations of the array of components **120** to calibrate the measuring circuit **100** and to perform measurements. Since electronic switches contain parasitic capacitance to ground that differs depending on whether they are open or closed, they may introduce unwanted capacitance into a circuit. In the measuring circuit **100**, it is desirable to have a fixed number of electronic switches while calibrating and measuring to minimize any changes of the parasitic capacitance. In that regard, the switching array **115** includes blank switches which are identical to the other switches in the switching array **115**, but only connect the sensing node to empty pads on the printed circuit board. This maintains a fixed number of open and closed switches, which results in a consistent offset capacitance. The switching array **115** is controlled such that when a switch to one component (or the sensor **125**) is closed, one blank switch (e.g., BL**1**) is open, and when two switches to two components are closed, both blank switches (e.g. BL**1** and BL**2**) are open.

The current source **105** supplies alternating current (AC) through the sensing node **110** to a sensing component **130**. In some embodiments, the sensing component **130** is a resistor having a known, or fixed, resistance value. The sensing component **130** is connected to the sensing node **110** on a first end and to ground on a second end. This configuration creates a voltage across the sensing component **130** that is dependent on the position of the switches of the switching array **115**. The sensing node **110** is connected to a buffer amplifier **135** that forms the input to a monitoring circuit **140** included within the larger measuring circuit **100**.

In one embodiment, the monitoring circuit **140** utilizes a synchronous demodulation circuit with gain and offset adjustment. The monitoring circuit **140** includes a buffer amplifier **135**. The output of the buffer amplifier **135** is connected to an input of a mixer **145**. The mixer **145** multiplies the signal from the buffer amplifier **135** with a variable-phase waveform, for example, a variable-phase square wave. The variable-phase waveform is supplied by a phase shifter **150**. The output of the mixer **145** is connected to a low-pass filter **155**, and the output of the low-pass filter **155** is connected to a gain and offset adjustment module **160**. The output from the gain and offset adjustment module **160** is connected to an analog-to-digital converter **165** for use as a digital signal in a controller or similar electronic processor.

In some embodiments, the phase shifter **150** includes circuitry for the conversion of an oscillating waveform into another oscillating waveform (e.g., a sine wave into a square wave). In one example, the phase shifter **150** includes a sine wave to square wave comparator and a circuit to delay the square wave by a controlled interval of time. In particular, a clock or a controlled number of discrete delay stages may be used to provide the delay and, thus, the phase shift. In another example, the phase shifter **150** inputs multiple sinusoids at the same frequency and sums the sinusoids together to form an intermediate-phase sinusoid. In this example, the phase shifter **150** adjusts the amplitude of one of the input sinusoids to vary the phase of the intermediate-phase sinusoid to create a variable-phase sinusoid. This variable-phase sinusoid is then converted into a square wave for input to the mixer **145**. In some embodiments, the mixer **145** is configured to perform sine wave mixing or other demodulation schemes that separate components of a signal based on their phase.

During operation of the measuring circuit **100**, an oscillating current from the current source **105** is divided among several parallel-type pathways. In one example, a portion of the current may flow to the switching array **115** and through the array of components **120** depending on the state of the switching array **115**. The current may also flow through the sensor **125** depending on whether the sensor **125** is connected by the switching array **115**. The current also flows through the sensing component **130** to ground. When the impedance of the switched-in components of the array of components **120** is lowered, the current through the sensing component **130** is lowered, and thus the voltage across the sensing component **130** is lowered. This reduces the voltage seen by the mixer **145**. When the switch to the sensor **125** is closed, a loss of current to the sensing component **130** occurs and this lowers the voltage seen by the mixer **145**. In this way, a change in voltage or in the phase angle of the voltage across the sensing component **130** can be used to identify the impedance, the resistance, and/or the reactance of the sensor **125**. In an ideal system, the in-phase component of the voltage (i.e., in-phase with the current) on the sensing component **130** acts as an indicator of the current due solely to resistance (i.e., resistive current) between the

current source **105** and ground. The quadrature component (i.e., a 90° phase shift from the in-phase component) acts as an indicator of the current due solely to a reactive impedance (i.e., reactive current) between the current source **105** and ground. However, in practice, the impedance from the current source **105** to ground is a mix of resistive and reactive impedances. As a consequence, the phase angle between the voltage and the current will not be exactly 0° or 90°.

FIGS. **2**A-**2**D illustrate a model and various aspects of the sensor **125**. FIG. **2**A is a schematic representation of the sensor **125**. FIG. **2**B schematically illustrates one implementation of the sensor **125**. FIGS. **2**C and **2**D illustrate another implementation of the sensor **125**. FIGS. **3**A-**3**B illustrate electrical models of the sensor **125**.

In the embodiments illustrated in FIG. **2**A-**2**C, the sensor **125** includes two electrodes, a first electrode **205**, **205**B, **205**C and a second electrode **210**, **210**B, **210**C. In the embodiment illustrated in FIG. **2**B, the first electrode **205**B is covered by a spherical dome (e.g., a conductive cage). In this case, the spherical dome constitutes the second electrode **210**B. In one embodiment, the second electrode **210**B is formed of a screen with numerous apertures that allow fluid to pass through the second electrode **210**B. In another embodiment (not shown), the second electrode **210**B is formed from a contiguous sheet or solid piece of material, but is configured with a small number of apertures to allow for some fluid movement. In other embodiments, the sensor **125** may include one or more conductors that arch above a sensing electrode. For example, the embodiment of sensor **125** illustrated in FIG. **2**C, includes the first electrode **205**C, a second electrode **210**C, and a mounting surface **215**C. The mounting surface **215**C may be formed of a printed circuit board (PCB). In this example, the second electrode **210**C arches above the first electrode **205**C. This allows fluid to flow between the first electrode **205**C and the second electrode **210**C. FIG. **2**D is a perspective view of the sensor illustrated in FIG. **2**C. It should be noted that the shape of the sensing or second electrode **210**, **210**B and **210**C can be different from the shapes illustrated and may take other forms. The sensor **125** may be made of conductive material including, for example, stainless steel, which is generally resistant to corrosion.

FIG. **3**A illustrates an electrical model of the sensor **125** and the fluid being sensed. This model takes into account both the electrical characteristics (e.g., conductivity and dielectric constant) of the fluid between the first electrode **205** and the second electrode **210** and the geometry of the sensor **125**. For example, the capacitance **220** represents the capacitance of the sensor **125** and the influence on that capacitance by the fluid in the sensor **125**. Similarly, the resistance **225** represents the resistance of the sensor **125** and the influence on that resistance by the fluid in the sensor **125**. Since the geometry of the sensor **125** is fixed, the capacitance **220** and the resistance **225** are values that indicate the fluid's dielectric constant and conductivity. FIG. **3**B illustrates another electrical model of the sensor **125** that includes capacitance due to a surface layer being formed or deposited on the electrodes. In this model, a first electrode capacitance **230** represents the capacitance of a surface layer on the first electrode **205**. The first electrode capacitance **230** reduces the total capacitance of the sensor **125**. Similarly, a second electrode capacitance **235** represents the capacitance of a surface layer on the second electrode **210**. The second electrode capacitance **235** reduces the total capacitance of the sensor **125**. FIG. **3**C represents a simplified electrical model of the sensor **125** of FIG. **3**B. In the simplified model, an induced capacitance **240** represents the combination of the first electrode capacitance **230** and the second electrode capacitance **235**. As the thickness of the surface layers increases, the induced capacitance **240** decreases. A decrease in the induced capacitance **240**, reduces the total capacitance of the sensor **125**. If the induced capacitance **240** due to the surface layers is small (corresponding to thick surface layers), the total capacitance (i.e., measured capacitance) of the sensor **125** will be strongly dependent on the thickness of the surface layer.

When the induced capacitance **240** is greater (e.g., **5** orders of magnitude greater) than the capacitance **220**, accurate measurements of the capacitance **220** can be made even when the resistance **225** is relatively low. However, as the induced capacitance **240** decreases (due to thicker surface layers) relative to the capacitance **220**, errors in measurement of the capacitance **220** may arise. Measurements at high frequencies (e.g., 10 MHz) may reduce the effect of this error. Conversely, measurements at low frequencies may produce errors that are dependent on the resistance, the induced capacitance **240**, and the frequency. The relationship between the error and the frequency may be expressed as shown in Equation 1, below.

$$\text{Error} = MCL - ACL \propto \frac{1}{frequency^2} \tag{1}$$

where MCL is the measured capacitance of the sensor **125** and ACL is the capacitance **220**. If measurements are made at two different frequencies, f1 and f2, the relationship in Equation 2 is true.

$$\frac{Error_{f1}}{Error_{f2}} = \frac{MCL_{f1} - ACL}{MCL_{f2} - ACL} \propto \frac{\frac{1}{f1^2}}{\frac{1}{f2^2}} = \frac{f2^2}{f1^2} \tag{2}$$

If measurements are made at two frequencies within a short period of time, the induced capacitance **240** and the resistance **225** may be considered constant values and the following equality in Equation 3 can be assumed.

$$\frac{MCL_{f1} - ACL}{MCL_{f2} - ACL} = \frac{f2^2}{f1^2} \tag{3}$$

The capacitance **220** may be described as shown in Equation 4.

$$ACL = \frac{\left(\frac{f2}{f1}\right)^2 * MCL_{f2} - MCL_{f1}}{\left(\frac{f2}{f1}\right)^2 - 1} \tag{4}$$

Therefore, even with a moderate surface layer on the electrodes **205** and **210**, measurements at two frequencies can be used to calculate the capacitance **220**. However, as the surface layer increases in thickness, the error in the measurement of capacitance across the sensor **125** becomes too large for the correction described above to work, especially when the resistance across the sensor **125** becomes small. As

described in greater detail below, in one embodiment, supplemental capacitors are used to match the reference impedances to the impedance of the sensor **125** to compensate for surface layers on the electrodes (See FIG. **16**).

FIG. **4** illustrates an exemplary controller **300** (e.g., a microcontroller, microprocessor, electronic processor, or similar device or group of devices). In the embodiment illustrated, the controller **300** includes a processing unit **305**, a memory **310**, a sensor configuration control **315**, a measurement configuration control **320**, a clock **325**, and the analog-to-digital converter **165**. The controller **300** is electrically connected to an alternative embodiment of the measuring circuit **100**. In the example illustrated, controller **300** is connected to a sensor multiplexer **335** and a signal conditioning module **360**. The sensor multiplexer **335** can be used as, or in lieu of, the switching array **115**. The controller **300** includes combinations of hardware and software that are operable to, among other things, control the operation of the measuring circuit **100**, control the sensor configuration control **315**, and control the measurement configuration control **320**. Additionally, the controller **300** is connected through the sensor multiplexer **335** to the sensor **125**, an optional fluid level sensor **350**, and the array of components **120** (Z**1**, Z**2**, . . . Zn).

The processing unit **305**, the memory **310**, the sensor configuration control **315**, the measurement configuration control **320**, as well as the other various components are connected by one or more control or data buses or both. The use of one or more control or data buses or both for the interconnection between and communication among the various components would be known to a person skilled in the art in view of the description and drawings provided.

The memory **310** includes a program storage area and a data storage area. The program storage area and the data storage area can include combinations of different types of memory **310**, such as machine-readable non-transitory memory, read-only memory ("ROM"), random access memory ("RAM") (e.g., dynamic RAM ["DRAM"], synchronous DRAM ["SDRAM"], etc.), electrically erasable programmable read-only memory ("EEPROM"), flash memory, a hard disk, an SD card, or other suitable magnetic, optical, physical, or electronic memory devices. The processing unit **305** is connected to the memory **310** and executes software instructions that are capable of being stored in a RAM of the memory **310** (e.g., during execution), a ROM of the memory **310** (e.g., on a generally permanent basis), or another non-transitory computer readable medium. Software included for the processes and methods for the measuring circuit **100** can be stored in the memory **310** of the controller **300**. The software can include firmware, one or more applications, program data, filters, rules, one or more program modules, and other executable instructions. For example, a method **500** (as shown in FIG. **6**) effectively stores information in EEPROM about the absolute values of C**1** and C**2** and the geometry of the sensor **125**. The processing unit **305** is configured to retrieve from memory **310** and execute, among other things, instructions related to the control processes and methods described herein. In other constructions, the controller **300** includes additional, fewer, or different components.

FIG. **5** illustrates the phase shifter **150** and the connections of the phase shifter **150** to the measuring circuit **100** according to one embodiment. The phase shifter **150** includes a divide and phase splitter **405** having two output connections. A first output of the divide and phase splitter **405** is connected to a first low-pass filter **410** and a second output of the divide and phase splitter **405** is connected to a second low-pass filter **415**. An output of the first low-pass filter **410** is connected to an input of the current source **105**, an input to a first operational amplifier **420**, and an amplitude controller **425**. An output of the first operational amplifier **420** is connected through a resistor (2R) to an input of a summation module **440**. The output of the amplitude controller **425** is connected to an input of a second operational amplifier **430**. The output of the second operational amplifier **430** is connected through a resistor (R) to an input of the summation module **440**. The output of the second low-pass filter **415** is connected to a third operational amplifier **435**, and the output of the third operational amplifier **435** is connected through a resistor (R) to an input of the summation module **440**. The output of the summation module **440** is connected to the positive terminal of a comparator circuit **445**. The output of the comparator circuit **445** is connected to the measuring circuit **100** at the input of the mixer **145**.

The phase shifter **150** manipulates the response of the measuring circuit **100** by producing a plurality of phases for measurements. This can be used to create a measurement space where the signal changes caused by increases in resistive current are approximately the same amplitude and approximately orthogonal to small changes in the capacitive current. The measurement space is created by separately mixing a signal from the measurement circuit with two signals that have phases that are near to each other and are on either side of the phase angle 90° away from the angle of the current change when there is a change of resistance between the sensing node and ground. For example, if the phase angle of the current change when a resistor is connected to the sensing node is 45°, then the two phases used for a measurement might be 130° and 140° (i.e. 45°+85°=130° and 45°+95°=140°). This allows measurement of the capacitance and the resistance of the sensor **125** at the same time even when the resistive current through the sensor **125** parallel to the capacitance is unknown and may be much larger than the capacitive current through the sensor **125**.

FIG. **6** is a flowchart illustrating an exemplary method **500** of determining the desired phase angles for the measuring circuit **100**. Although illustrated in sequential order, steps of method **500** may be performed sequentially, simultaneously, or in a different order. The method **500** can be performed, at least in part, by the controller **300**. It is possible to also perform portions of the method **500** manually. To begin, the blank switches (i.e., BL**1** and BL**2**) are closed, all other switches of the switching array **115** are opened, and the power is turned on (step **505**). The phase shifter **150** is adjusted, by the controller sending an adjustment signal, to a first phase (Phase**1**) (step **510**). The offset of the gain and offset adjustment module **160** is adjusted such that the output of the analog-to-digital converter **165** is in the middle of the output range of the analog-to-digital converter **165** (i.e., the output of the signal conditioning module **360**) and the output is recorded (OUT**1**) (step **515**). The phase shifter **150** is adjusted to a second phase (Phase**2**), which may be close to Phase**1** (e.g., six degrees above Phase**1**) (step **520**). Then, the offset of the gain and offset adjustment module **160** is adjusted such that the output of the analog-to-digital converter **165** is in the middle of the output range of the analog-to-digital converter **165** and the output is recorded (OUT**2**) (step **525**). For a given set of steps, step **505** to step **540**, Phase**1** and Phase**2** each have their own respective offset adjustment which may remain fixed for the measurement sequence. A blank switch (e.g., BL**1**) is opened and the switch for R**1** is closed (step **530**). Outputs (R**11**, R**12**) of the analog-to-digital converter **165**

for both Phase1 and Phase2 are recorded using their respective offset adjustments (step **535**). A slope of a slope of a line between the outputs (OUT1, OUT2) and the outputs (R11, R12) is calculated (step **540**).

Once calculated, a determination of whether the slope is positive is made (step **545**). If the slope is positive, a blank switch (e.g., BL1) is closed, the switch for R1 is opened, and steps **510** through **540** are repeated (step **550**). When step **510** and step **520** are triggered from step **550**, the phase adjustments for Phase1 and Phase2 may be increased by a moderate amount, for example, approximately 3°. After repeating steps **510** through **540**, the method returns to step **545** and determines if the slope of the line between the adjusted output values (OUT1, OUT2) and (R11, R12) is positive. If the slope is not positive, a determination of whether the slope is approximately equal to −1 is made (step **555**). If the slope is not approximately equal to −1, a blank switch (e.g., BL1) is closed, the switch for R1 is opened, and steps **510** through **540** are repeated (step **560**). When step **510** and step **520** are triggered from step **560**, the phase adjustments for Phase1 and Phase2 may be increased by a slight amount, for example, by approximately 0.2°. After repeating steps **510** through **540**, the method returns to step **555** and a determination of whether the slope of the line between the adjusted output values (OUT1, OUT2) and (R11, R12) is approximately equal to −1 is made. If the slope is approximately equal to −1, the desired phase angles (Phase1 and Phase2) have been found (step **565**). As will be described in greater detail, in the example described, the phase angles determined in the method **500** are used in the measurement method **900** of FIG. **9**. It should be noted that the adjustments to the phase angles triggered by step **550** and step **560** may include additional logic that aids in determining the desired phase angles by estimating an amount and direction of phase angle change for step **510** and step **520**.

FIG. **7** is a graph illustrating an exemplary output of the signal conditioning module **360** for step **540** of the method **500**. The outputs are plotted in coordinate pairs representing the measurements made at Phase1 and Phase2. The coordinate pairs represent sets of calibration signals. First, the Phase1 and Phase2 outputs (OUT1, OUT2) are plotted with only the blank switches (i.e., BL1 and BL2) closed. The Phase1 and Phase2 outputs (R11, R12) are also plotted with the switch for R1 closed and a blank switch (e.g., BL1) open. The line illustrates the slope between the coordinate pairs (OUT1, OUT2) and (R11, R12) and can be calculated by the Equation 5.

$$\text{Slope} = \frac{R12 - OUT2}{R11 - OUT1} \tag{5}$$

FIG. **8** is a graph illustrating example adjustments on the Phase1 and Phase2 signals with the switch for R1 closed and a blank switch (e.g., BL1) open. The arrows represent changes in the output for changes in the Phase1 and Phase2 signals between successive measurements (step **550** or **560**). The coordinate pair (2.9, 2.1) depicts the target area where the slope is approximately equal to −1 from the coordinate pair without the resistor (R1) to the coordinate pair with the resistor (R1). Finding the phases where the slope is approximately −1 means that the average of Phase1 and Phase2 (i.e., (Phase1+Phase2)/2) is approximately the phase angle 90° from the angle of the change of the total current due to the current added when R1 is switched in. The negative slope is an indication that the two phases, Phase1 and Phase2, are on opposite sides of the phase angle 90° from the actual current change phase caused by switching in R1. Functionally, the two phases are chosen such that the output of the signal conditioning module **360** at one phase increases by approximately the same amplitude that the output at the other phase decreases when there is a parallel resistance switched in (e.g., R1). It should be noted that finding the phases where the slope is exactly −1 may not be necessary. Measurements may also be performed even when the calculated slope is significantly different than −1. As an example, a calculated slope anywhere in the range between −0.5 and −2 may give satisfactory results.

FIG. **9** is a graph illustrating an example of the change in the output voltage of the signal conditioning module **360** that occurs as a parallel capacitor (C1) of the array of components **120** is switched in. In this case, an increase in current to the array of components **120** due to switching in a small parallel capacitance will decrease the current to and the voltage across the sensing component **130**. For example, the coordinate pair (1.75, 1.75) of outputs of the signal conditioning module **360** for Phase1 and Phase2 has a lower voltage than the coordinate pair (2.5, 2.5) which does not have C1 switched in. The coordinate pair (1.75, 1.75) rests on a line with a slope of +1 to the coordinate pair (2.5, 2.5). FIG. **9** demonstrates that once the measuring circuit **100** is calibrated, switching the array of components **120** to add or remove purely capacitive components results in a change of the coordinates of the output of the signal conditioning module **360** such that the new coordinates will rest on a line with a slope of +1 from the previous coordinates. In other words, the measurement change due to an additional small parallel capacitance will lie on a line with a slope of +1, and the measurement change due to an additional parallel resistance will lie on a line with a slope of −1.

FIG. **10** is a flowchart illustrating an exemplary measurement method **900** for the capacitance **220** of the sensor **125**. Although illustrated in sequential order, steps of the measurement method **900** may be performed sequentially, simultaneously, or in a different order. In one example, measurement method **900** is performed at least in part by the controller **300**. It is possible to perform parts of the measurement method **900** manually. Throughout the method **900**, the gain and offset settings of the gain and offset adjustment module **160** are adjusted and the settings of the phase shifter **150** are adjusted to the settings determined in method **500** for each measurement (step **905**). A blank switch (e.g., BL1) is closed, the switch for C1 is closed, all other switches of the switching array **115** are opened, and the output voltage of the analog-to-digital converter **165** at Phase1 and at Phase2 is measured (step **910**). A blank switch (e.g., BL1) is closed, the switch for C2 is closed, all other switches of the switching array **115** are opened, and the output voltage of the analog-to-digital converter **165** at Phase1 and at Phase2 is measured (step **915**). In the next step, n is set equal to 1, where n corresponds to a particular one of the resistors (R1, R2, . . . Rn) in the array of components **120** (step **920**). The switch for Rn is closed, the switch for C1 is closed, all the other switches of the switching array **115** are opened, and the output voltage of the analog-to-digital converter **165** at Phase1 and at Phase2 is measured (step **925**). The switch for Rn is closed, the switch for C2 is closed, all other switches of the switching array **115** are opened, and the output voltage of the analog-to-digital converter **165** at Phase1 and Phase2 is measured (step **930**). In the next step, a determination of whether n equals n maximum (i.e., a highest numbered resistor) is made (step **935**). This determination provides an indication of whether

all the resistors in the array of components **120** have been used. If n does not equal n maximum, n is incremented by one (step **940**). The method then proceeds to step **925**. If n does equal n maximum, a blank switch (e.g., BL**1**) is closed, the switch for the sensor **125** is closed, all other switches of the switching array **115** are opened, and the output voltage of the analog-to-digital converter **165** at Phase**1** and at Phase**2** is measured (step **945**). As will be described in greater detail, the reference measurements and the measurement of the sensor **125** (i.e., the measurements of the output voltages) are used to calculate the capacitance of the sensor **125** (FIG. **13**).

FIG. **11** is a graph of an example of outputs of the measurement method **900** with only the output values generated with one resistor (R**1**) shown. Each graph will have different measured points depending on the reference values, the phase angles, the offset, and the gain of the system. The graph shown illustrates the measured outputs for the Phase**1** and Phase**2** signals (i.e., reference signals). Typically, the outputs are plotted for the coordinate pairs associated with each pairing of components from the array of components **120**. Each of these outputs provides a set of reference signals corresponding to a different configuration of the array of components. An electrical characteristic of the fluid may be determined by comparing differences in values between the reference signals and the sensor signals. This includes plotting C**1** and C**2** with every resistor (R**1**, R**2**, . . . Rn) and plotting C**1** and C**2** with a blank switch (i.e., BL**1** or BL**2**). Additionally, the resistors (R**1**, R**2**, . . . Rn) are plotted with a blank switch (i.e., BL**1** or BL**2**). FIG. **11** illustrates that the capacitance changes are plotted on a line along a +1 slope from the coordinate pair (Blank, Blank), and the resistance changes are plotted on a line along a −1 slope from the coordinate pair (Blank, Blank). For example, the output change between the (C**1**, Blank) measurement and the (R**1**, C**1**) measurement is due to a change in parallel resistance, while the output change between the (C**1**, Blank) measurement and the (C**2**, Blank) measurement is due to a change in parallel capacitance. This behavior allows the resistance and the capacitance components of the sensor **125** to be separated and individually calculated as shown in FIG. **13**.

FIG. **12** is a graph illustrating parallel lines of fixed capacitance. As in FIG. **11**, the graph illustrates the coordinate pairs of the outputs for the Phase**1** and Phase**2** signals for a plurality of components in parallel. The coordinate pairs create reference points to determine lines of fixed capacitance. For example, the coordinate pairs (C**1**, Blank) and (R**1**, C**1**) have the same capacitor, but the coordinate pair (R**1**, C**1**) adds a resistor (R**1**). A line that connects (C**1**, Blank) and (R**1**, C**1**) demonstrates a change in the components purely due to resistance, and therefore, represents a line of fixed capacitance. Similarly, a line that connects (C**2**, Blank) and (R**1**, C**2**) is a line of fixed capacitance. Lines of fixed resistance can also be determined. For example, a line of fixed resistance lies between the points (R**1**, C**1**) and (R**1**, C**2**).

FIG. **13** is a graph illustrating interpolation between the lines of fixed capacitance for determining the capacitance of the sensor **125** according to one embodiment. Since the capacitance values for C**1** and C**2** are known, the capacitance values represented by the lines of fixed capacitance are also known. The capacitance of the sensor **125** is calculated by interpolating between the lines of fixed capacitance. This calculation can performed using Equation 6.

$$Csensor = L1 * \frac{C2 - C1}{L1 + L2} + C1 \tag{6}$$

Where L**1** and L**2** are the distances from the lines of fixed capacitance to the measurement point of the sensor **125** and C**1** and C**2** are the capacitances in Farads of the reference capacitors. The calculation of the capacitance of the sensor **125** can be performed in a variety of ways once the measurements are performed. This equation is an example of one of the equations that can perform the interpolation, but the invention is not limited to this equation. It is also possible to use a single reference capacitor to make a measurement. In that case, a line of fixed capacitance extends between the points (Blank, Blank) and (R**1**, Blank). This line is a line of fixed capacitance of roughly zero. As noted above, a line of fixed capacitance extends between (C**1**, Blank) and (C**1**, R**1**). In this case, L**1** is the distance between the line of roughly zero capacitance and the coordinate pair (Sensor, Blank), and L**2** is the distance between the other line of fixed capacitance (for C**1**) and the coordinate pair (Sensor, Blank). In this case, the equation to calculate the capacitance of the sensor **125** simplifies to Equation 7.

$$Csensor = \frac{L1 * C1}{L1 + L2} \tag{7}$$

The conductivity of the sensor **125** can also be measured with similar algorithms that use interpolation between lines of fixed resistance. For example, when each of the multiple resistors (R**1**, R**2**, . . . Rn) of the array of components **120** is switched in, a total resistance seen by the current source **105** may be calculated as shown in Equations 8 and 9.

$$Rtotalhigh = \frac{R * Rhigh}{R + Rhigh} \tag{8}$$

$$Rtotallow = \frac{R * Rlow}{R + Rlow} \tag{9}$$

Where R is a value of the resistance of the sensing component **130**, Rhigh is the value of a resistor of the array of components **120** that corresponds to a line of fixed resistance with a higher value of resistance than the value of a resistance of the sensor **125**, and Rlow is the value of a resistor of the array of components **120** that corresponds to a line of fixed resistance with a lower resistance than the sensor **125**.

After the phases, offsets, and gain are determined, the distance is determined, in measurement units, between the line of fixed resistance that corresponds to the higher value of resistance and the measurement of the sensor **125** to find D**1**. Similarly, the distance is determined, in measurement units, between the line of fixed resistance that corresponds to the lower value of resistance and the measurement of the sensor **125** to find D**2**. The resistance of the sensor **125** in combination with the resistance of the sensing component **120** may then be determined by interpolation between the lines of fixed resistance as shown in Equation 10.

$$Rcombined = Rtotalhigh - \frac{D2 * (Rtotalhigh - Rtotallow)}{D1 + D2} \tag{10}$$

The resistance of the sensor **125** may then be determined as shown in Equation 11.

$$Rsensor = \frac{R * Rcombined}{R - Rcombined} \quad (11)$$

Since the conductivity of the sensor **125** is not known prior to measurement, the plurality of resistors of the array of components **120** enables the measuring circuit **100** to measure capacitance of the sensor **125** over a large range of conductivities. This allows the system to focus the measurement space on values close to the actual values of the resistance and capacitance of the sensor **125**. With a small enough resistor value, the measuring circuit **100** can achieve measurements when conductivities are well over 1000 μS/cm. A full measurement map characterizes the measurement system around, and near to, any values of the sensor **125**. This results in an accurate capacitance measurement for various liquids even if their conductivities differ by more than a factor of one hundred.

FIG. **14** illustrates a change in output voltage over a wide range of parallel resistances according to one embodiment. Two lines of fixed capacitance are represented by two lines in the graph. The resistances range from 50Ω on the right side of the graph to 10^9Ω on the left side of the graph. As illustrated by approaching lines of fixed capacitance, the measurement space narrows as the parallel resistances get smaller. This causes a reduction in resolution at low parallel resistances. However, the gain and offset adjustment module **160** increases resolution and thus compensates for the loss of resolution. As shown in the graph, the lines of fixed capacitance can be straight or curved over a wide range of resistances. Using a plurality of reference resistors (e.g., R**1**, R**2**, etc.) in the array of components **120** that are in the range of resistances of the measurements reduces the effect of curvature of the lines of fixed capacitance. The lower the distance between lines of fixed resistance, the less error will be caused by a calculation based on the line segments of the lines of fixed capacitance. In this way, the curvature of the fixed lines of capacitance depend on the available levels of impedance of the array of components **120**.

FIG. **15** illustrates an embodiment that compensates for the curvature of the lines of fixed capacitance. An inductor **1405** (e.g., 100 nH to 10,000 nH) is added between the sensing node **110** and the switching array **115**. The inductor **1405** straightens out the curvature of the lines of fixed capacitance over a wide range of resistances, thereby improving straight-line approximation. Other embodiments have different additional components that are used to modify the response of the system. For example, an inductor **1405** may be added in series with the array of components **120** to adjust for inductance created by long leads to the sensor **125**. In some embodiments, the algorithm to calculate capacitance using interpolation takes the curvature of the lines of fixed capacitance into account. For example, the curvature between the reference point measurements can be approximated by using measured values of three successive points at each line of fixed capacitance and deriving an appropriate curve for each line that passes through the measured points and that has a constant slope on either side of the center measurement point. If should be noted that multiple algorithms may be used to obtain a straight-line approximation of the lines of fixed capacitance.

FIG. **16** is a block diagram of another embodiment of a measuring circuit **1500**. The measuring circuit **1500** includes a current supply **1505** connected to a sensing node **1510**, a switching array **1515**, an array of components **1520**, and a sensing component **1530** (e.g., a resistor). The measuring circuit **1500** also includes a buffer amplifier **1535**, a mixer **1545**, a low-pass filter **1555**, a gain and offset module **1560**, and an analog-to-digital converter **1565**. In these respects, the measuring circuit **1500** is similar to the measuring circuit **100**. However, the measuring circuit **1500** includes multiple switchable impedances in a series-type connection with the array of components **1520**. In particular, the measuring circuit **1500** includes an inductance switching array **1570**, an array of inductors **1575**, a series inductor **1580**, a capacitance switching array **1585**, an array of capacitors **1590**, and a sensor switching array **1595**.

The inductance switching array **1570** is controllable by the controller **300** to select various inductance values from the array of inductors **1575** to place in a series-type connection with the array of components **1520** and the sensor switching array **1595**. Similarly, the capacitance switching array **1585** is controllable by the controller **300** to select various capacitance values from the array of capacitors **1590** to place in a series-type connection with the array of components **1520**. The sensor switching array **1595** is controllable by the controller **300** to select either a sensor **1525** or a blank switch (e.g., BL**3**). In addition, the series inductor **1580** is connected between the array of inductors **1575** and the capacitance switching array **1585**.

The measuring circuit **1500** is able to compensate for low levels of total capacitance across the sensor **125** caused by low values of induced capacitance **240** on the sensor **125** (see FIG. **3**C). When the induced capacitance **240** becomes so low such that the reference impedances of the array of components **1520** no longer have absolute values similar to the total capacitance of the sensor **125**, the controller **300** switches in series capacitance using the capacitance switching array **1585**. The addition of capacitor CS**1** and capacitor CS**2** of the array of capacitors **1590** allow a capacitance to be inserted in series with the reference impedance from the array of components **1520**. In this way, the total impedance measured during the reference measurements is in a similar range as the total capacitance of the sensor **125**. The controller **300** is configured to determine which value of capacitance should be inserted in series with the array of components **1520** by making measurements and calculating the difference between the calculated capacitance at a first frequency and the calculated capacitance at a second frequency. For example, if the difference is above a threshold then the controller **300** switches in a smaller valued capacitor from the array of capacitors **1590**. Other algorithms may also be used to decide which capacitor should be inserted in series. In addition, the controller **300** switches the inductance switching array **1570** to place an inductor LS**1**, an inductor LS**2**, and an inductor LS**3** from the array of inductors **1575** in various combinations into a series-type connection with the array of components **1520** and the sensor switching array **1595**. The inductance switching array **1570** enables the controller **300** to match the appropriate series inductance with the selected series capacitance to straighten the response curves as discussed above.

It should be noted that the sensor switching array **1595** may be separate from the switching array **1515** and that the sensor switching array **1595** is switchable with its own blank switch BL**3**, as illustrated in FIG. **16**. When the reference impedances of the array of components **1520** are being measured, the blank switch BL**3** is closed and a sensor switch of the sensor switching array **1595** for switching in the sensor **1525** is open. When the sensor **1525** is being

measured, the blank switch BL3 is open, the reference blank switches, BL1 and BL2, are closed, and the sensor switch is closed. In this way, the measuring circuit **1500** controls the sensor switching array **1595** and the switching array **1515** such that the parasitic capacitance is held constant throughout the measurement method **900**.

It should be noted that although the circuit described here uses a current source **105**, a sensing component **130**, and a buffer amplifier **135** as the electronics used to create the measurement signal, other variations of measuring circuits may be used to create the measurement signal. For example, in some embodiments, an oscillating voltage source and an alternative method of measuring the sensing current may be used. The variable phase signal may then be mixed with the measurement signal as described by the methods disclosed herein.

It should also be noted that embodiments may also be used to measure the resistive and reactive components of impedances not associated with a fluid sensor. For example, embodiments may be used to measure the impedance of biological tissue or other industrial applications where a high frequency measurement is desired.

Once the capacitance of the sensor **125** is determined by using the above-described methods and circuits, the dielectric constant of the fluid can be calculated using Equation 12.

$$k = \frac{C_{sensor} - C_{offset}}{X} \tag{12}$$

The C_{offset} is the portion of the measured capacitance that does not change with the dielectric constant. X is determined by measuring a capacitance of the sensor **125** with each of two fluids of known dielectric constant (k1 and k2). $C_{sensor1}$ is a capacitance of the sensor **125** when the first fluid is measured and $C_{sensor2}$ is the capacitance of the sensor **125** when the second fluid is measured. X may be determined using Equation 13.

$$X = \frac{C_{sensor1} - C_{sensor2}}{k1 - k2} \tag{13}$$

The dielectric constant of the fluid may then be used to determine other characteristics of the fluid. For example, the concentration or quality levels of the fluid.

Thus, the invention provides, among other things, a system and a method for determining capacitance and resistance of a fluid sensor, especially when a low-resistance path lies in parallel to the capacitance. Various features and advantages of the invention are set forth in the following claims.

What is claimed is:

1. A system for measuring an electrical characteristic of a fluid by separating a first orthogonal component of a signal change of a measurement signal and a second orthogonal component of the signal change of the measurement signal, where the first orthogonal component is due to a change in resistance across a sensor and the second orthogonal component is due to a change in capacitance across the sensor, the system comprising:

an array of components including the sensor;

a mixer that mixes the measurement signal with a first phase signal and a second phase signal, the mixer outputting a first mixed signal related to the first phase signal and a second mixed signal related to the second phase signal; and

a controller that is configured to

receive a signal indicative of the first mixed signal and the second mixed signal;

control the array of components to cause the signal change;

adjust the first phase signal and the second phase signal such that when there is a change in the first orthogonal component, the first mixed signal is increased and the second mixed signal is reduced;

control the array of components to cause additional signal changes;

receive a plurality of mixed signals indicative of the additional signal changes at the first phase and the second phase;

determine the electrical characteristic of the fluid based on the plurality of mixed signals.

2. The system of claim **1**, wherein the electrical characteristic of the fluid is a dielectric constant and a conductivity of the fluid.

3. The system of claim **1**, wherein the controller is further configured to identify measures that are related to a dielectric constant and a conductivity of the fluid based on the plurality of mixed signals.

4. The system of claim **1**, wherein the controller is further configured to measure a resistance and reactance of the sensor based on the plurality of mixed signals.

5. The system of claim **1**, further comprising a phase shifter connected to the mixer, the phase shifter configured to output and adjust the first phase signal and the second phase signal based on an adjustment signal from the controller.

6. The system of claim **5**, wherein the controller is further configured to:

perform a calibration of the first phase signal and the second phase signal before determining the electrical characteristic of the sensor, wherein, during calibration, the controller is configured to

measure, at a first calibration impedance, a first calibration signal when the first phase signal is input to the mixer and a second calibration signal when the second phase signal is input to the mixer;

measure, at a second calibration impedance, a third calibration signal when the first phase signal is input to the mixer and a fourth calibration signal when the second phase signal is input to the mixer; and

adjust the first phase signal and the second phase signal based on the first calibration signal, the second calibration signal, the third calibration signal, and the fourth calibration signal.

7. The system of claim **1**, wherein the array of components includes a plurality of resistors.

8. The system of claim **1**, wherein the array of components includes at least one capacitor, at least one resistor, and at least one blank switch.

9. The system of claim **1**, further comprising a switchable array of capacitors in a series-type connection connected to the array of components.

10. The system of claim **9**, further comprising a switchable array of inductors in a series-type connection connected to the array of components.

11. The system of claim **10**, further comprising an offset inductor in a series-type connection connected between the array of inductors and the array of capacitors.

12. A method of measuring an electrical characteristic of a fluid with a measuring circuit that includes a sensing node, a sensor switchably connected to the sensing node, and an array of components switchably connected to the sensing node, and a controller, the method comprising:

mixing a signal indicative of a voltage at the sensing node at a first configuration of the array of components with a first phase signal and a second phase signal to create a first set of reference signals;

mixing the signal at a second configuration of the array of components with the first phase signal and the second phase signal to create a second set of reference signals;

adjusting the first phase signal and the second phase signal until a relationship between the first set of reference signals and the second set of reference signals satisfies a condition;

setting a plurality of configurations of the array of components;

mixing the signal with the adjusted first phase signal and the adjusted second phase signal at each of the plurality of configurations of the array of components to create a plurality of sets of reference signals;

mixing the signal with the adjusted first phase signal and the adjusted second phase signal with the sensor connected to the sensing node to create a set of measurement voltages;

determining the electrical characteristic of the fluid based on a relationship between the plurality of sets of reference signals and the set of measurement voltages.

13. The method of claim 12, wherein determining the electrical characteristic of the fluid includes identifying measures that are related to the dielectric constant and the conductivity of the fluid based on the relationship between the plurality of sets of reference signals and the set of measurement voltages.

14. The method of claim 12, wherein determining the electrical characteristic of the fluid includes determining a resistance and a reactive impedance of the sensor based on the plurality of sets of reference signals and the set of measurement voltages.

15. The method of claim 12, wherein adjusting the first phase and the second phase until a relationship between the first set of reference signals and the second set of reference signals satisfies a condition includes determining when a voltage change between the first set of reference signals and the second set of reference signals indicates a resistance change orthogonal to a capacitance change.

16. The method of claim 12, wherein adjusting the first phase and the second phase until a relationship between the first set of reference signals and the second set of reference signals satisfies a condition includes determining a slope of a line extending between the first set of calibration voltages and the second set of calibration voltages.

17. The method of claim 16, wherein the relationship is having a line between the first set of calibration voltages and the second set of calibration voltages with a slope approximately equal to −1.

18. The method of claim 12, further comprising:

mixing the signal at a third configuration of the array of components with the first phase signal and the second phase signal to create a third set of reference signals;

mixing the signal at a fourth configuration of the array of components with the first phase signal and the second phase signal to create a fourth set of reference signals;

mixing the signal at a fifth configuration of the array of components with the first phase signal and the second phase signal to create a fifth set of reference signals;

mixing the signal at a sixth configuration of the array of components with the first phase signal and the second phase signal to create a sixth set of reference signals; and

determining the electrical characteristic of the fluid by comparing a difference in value of the set of sensor voltages with the third set of reference signals, the fourth set of reference signals, the fifth set of reference signals, and the sixth set of reference signals.

19. The system of claim 18, wherein determining the electrical characteristic of the fluid by comparing a difference in value of the set of sensor voltages with the third set of reference signals, the fourth set of reference signals, the fifth set of reference signals, and the sixth set of reference signals includes

determining a first line of fixed capacitance between the third set of reference signals and the fourth set of reference signals;

determining a second line of fixed capacitance between the fifth set of reference signals and the sixth set of reference signals; and

determining a capacitance of the sensor by interpolating between the first line of fixed capacitance and the second line of fixed capacitance.

20. A system for measuring an electrical characteristic of a fluid, the system comprising:

a sensing node;

a sensor connected, via a switching array, to the sensing node;

an array of components connected, via the switching array, to the sensing node, the array of components including a plurality of impedances;

a monitoring circuit connected to the sensing node, the monitoring circuit configured to input a plurality of signals at a plurality of phases and output a signal related to a measurement signal at the sensing node; and

a controller connected to the switching array and the monitoring circuit, the controller configured to

receive the plurality of signals,

set a first phase and a second phase of an input signal to the monitoring circuit;

measure, at a first calibration impedance of the plurality of impedances, a first calibration voltage at the first phase and a second calibration voltage at the second phase;

measure, at a second calibration impedance of the plurality of impedances, a third calibration voltage at the first phase and a fourth calibration voltage at the second phase;

adjust the first phase and the second phase until a relationship between the first calibration voltage, the second calibration voltage, the third calibration voltage, and the fourth calibration voltage satisfies a condition;

adjust the plurality of impedances by controlling the switching array to connect at least one component of the array of components to the sensing node in a parallel-type connection,

determine a first set of reference signals based on the signal when the switching array is configured to couple a first measuring impedance of the plurality of impedances to the sensing node;

determine a second set of reference signals based on the signal when the switching array is configured to couple a second measuring impedance of the plurality of impedances to the sensing node;

determine a set of sensor voltages based on the signal when the switching array is configured to couple the sensor to the sensing node, and

determine an electrical characteristic of the sensor based on the first set of reference signals, the second set of reference signals, and the set of sensor voltages.

* * * * *